VOLUME XXVII NUMBER 4

THE

JOURNAL OF GEOLOGY

MAY-JUNE 1919

THE BUILDING OF THE COLORADO ROCKIES

ROLLIN T. CHAMBERLIN
The University of Chicago

PART II

THE LYONS–GRAND RIVER SECTION

After a consideration of alternative locations for the contemplated study of the Colorado Rocky Mountain diastrophism, a section across the folded belt between the Great Plains north of Denver and the Uinta Basin west of Glenwood Springs was selected as offering the most promise. Among the advantages thus offered, it may be noted that this section would bring in the characteristic *en échelon* structure of the eastern foothills, here specially declared;[1] it would cross the Front Range where strongly developed; it would embrace the wide area of sedimentary rocks in Middle Park; it would traverse a typical section of the Park Range, and finally beyond this it would extend across the most representative strip of the slightly disturbed sedimentary belt to the Grand Hogback which terminates the Rocky Mountain folding on the west. Such a section, furthermore, would be across one of the wider portions of the Colorado Rockies. There was a further advantage growing out of the fact that the Colorado Rockies

[1] This has recently been described by Victor Ziegler, "Foothills Structure in Northern Colorado," *Jour. Geol.*, XXV (1917), 715–40.

embrace extensive areas of pre-Cambrian granite and other crystalline rocks. Over such areas of old crystalline rocks it is difficult to reconstruct the folds, since these areas afford only the most meager information as to the nature of the post-Cretaceous folding and as a result are little better than blank pages in the later diastrophic story. It was therefore advisable to choose a section which, though it be typical of the mountain system as a whole,

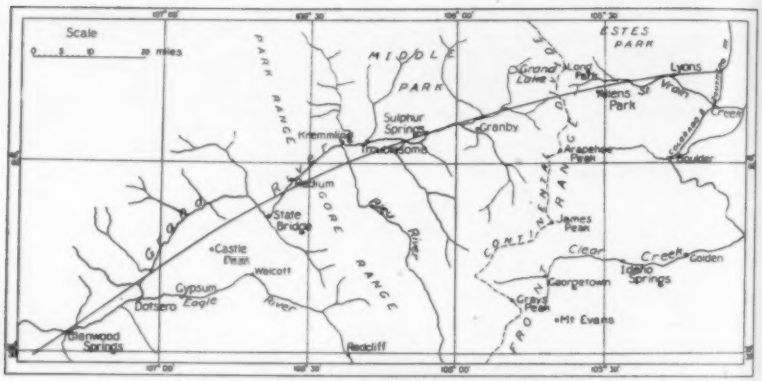


FIG. 4.—Map of the Lyons–Grand River section. The section extends along a curved line from the Colorado and Southern Railroad east of Lyons, to the western slope of the Grand Hogback southwest of Glenwood Springs, a total distance of 135 miles. Because of the adopted curvature the line of the section crosses the axial lines of the folds approximately at right angles.

still crossed the granite belts where they are narrowest, and where the belts of folded sedimentary rocks are widest. This was accomplished in the section chosen.

The section finally selected for measurement has as its eastern terminus the bend of the Colorado and Southern Railroad tracks, $4\frac{1}{2}$ miles north of the town of Longmont (Niwot sheet, T. 3 N., R. 69 W., Sec. 11, middle of S. line). From this point westward the line of section was drawn so as to strike the bench mark (5,375 feet) in the town of Lyons, to pass onward through Allen's Park, and across the continental divide one-fifth of a mile north of Oglala Peak (13,147 feet). On the Pacific slope it continues west-

ward in the general vicinity of the Grand River, runs by the railroad station at Hot Sulphur Springs, passes 2⅓ miles north of State Bridge, and finally crosses the city of Glenwood Springs and the

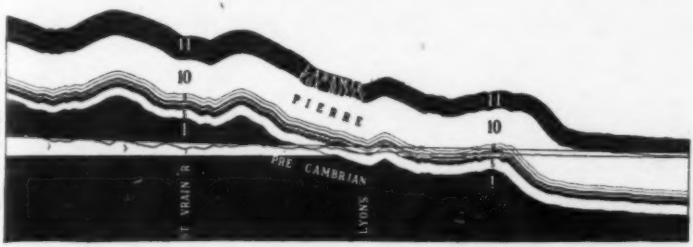


FIG. 5.—Lyons sheet (No. 1) on the east and St. Vrain sheet (No. 2) on the west. The restored folds include all beds to the top of the Laramie. The principal formations are: (1) pre-Cambrian granite; (5) Fountain and Lyons sandstones; (6) Lykens (red beds); (7) Morrison; (8) Dakota; (9) Benton and Niobrara; (10) Pierre; (11) Fox Hills and Laramie. The layers have been left unshaded throughout a horizontal strip whose base represents a level 5,000 feet above the sea, and whose top is the tilted peneplain surface. The profile of the present land surface is represented by a line which lies for the most part within this unshaded strip. Each sheet represents a horizontal distance of ten miles. (Total = 20 miles)

FIG. 6.—Allen's Park sheet (No. 3) on the east and Continental Divide sheet (No. 4) on the west. The peneplain here reaches its greatest elevation. A few monadnocks rise above the bowed peneplain and today constitute the high peaks of the Front Range. Fig. 6 represents a horizontal distance of twenty miles.

Grand Hogback to the flat-lying strata of the Uinta Basin, 6¼ miles southwest of Glenwood Springs (Fig. 4).

The trace of this section drawn on the map is not a straight line, for it was purposely given a slight curvature that it might cross

the trends of the different folds as nearly at right angles as possible. This curvature was necessitated by the fact that the individual ranges are not parallel to one another, but converge toward the south. The curved section crossing these ranges at right angles, and hence also normal to the axial lines of the folds, has its convex

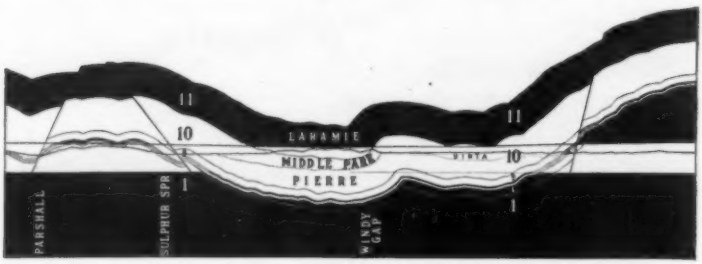


FIG. 7.—Granby sheet (No. 5) on the right and Sulphur Springs sheet (No. 6) on the left. The Middle Park (early Tertiary) beds occupy a part of the structural basin between Windy Gap and Sulphur Springs while the Uinta beds appear in the lesser basin in the middle of the Granby sheet.

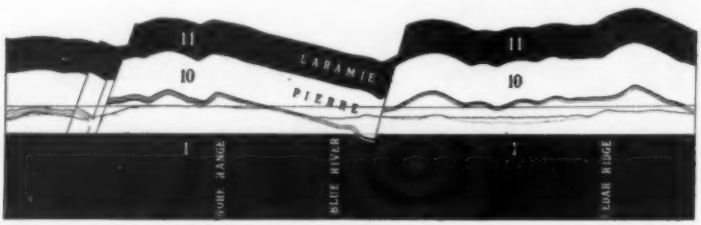


FIG. 8.—Troublesome sheet (No. 7) on the east and Gore Range sheet (No. 8) on the west. The formations are: (1) pre-Cambrian granite; (6) Red Beds; (7) Morrison; (8) Dakota; (9) and (10) Colorado and Pierre; (11) Fox Hills and Laramie. Basin of Uinta beds in the middle of the Troublesome sheet. The peneplain rests upon the broad crest of the Gore Range.

side therefore facing northwest. The total length of the section measured on this slight curve is 135 miles.

The topographic sheets of the United States Geological Survey as yet cover only the eastern portion of this selected section. Here the Niwot, Boulder, and Long's Peak sheets were a great help in locating the field observations and in plotting the cross-section. West of

the Long's Peak quadrangle, one had to be satisfied with the land surveyor's map of Grand County and the Department of Agriculture's Forest Service map of the Holy Cross National Forest, which together cover the remainder of the section.

Throughout this section of 135 miles, the dips of the strata were read wherever obtainable, and were plotted to scale as the

FIG. 9.—State Bridge sheet (No. 9) on right and Castle Peak sheet (No. 10) on left. Formations: (1) pre-Cambrian; (2) Sawatch; (4) Blue limestone; (5) Weber and Maroon formations; (6) Red Beds; (7) Morrison; (8) Dakota; (9) and (10) Mancos; (11) Mesa Verde.

FIG. 10.—Gypsum sheet (No. 11) on the right and Dotsero sheet (No. 12) on the left. The peneplain level appears high above the present surface because this section is within the Grand River Valley. Conventions as before.

basis for the reconstruction of the original folded structure. Compared with the Pennsylvania Appalachians, the Colorado Rockies present greater obstacles to an investigation of this sort, because it is impossible to obtain equally complete data. In the Appalachians of Pennsylvania the sedimentary beds still persist throughout the mountainous region to such an extent that from the remnants the original outlines of the folds may be reconstructed with the assurance of reasonable accuracy. But among the Colorado

Rockies the deformed sedimentary strata, to which one must look for the record of the folding, have been completely removed from large areas by the great denudation which the region has suffered. In those areas the pre-Cambrian granites and gneisses now constitute the surface formation. Over such crystalline areas folds can be projected only diagrammatically and a large element of error, or at least of uncertainty, is necessarily involved. In Middle Park, sediments of Uinta age, deposited after the folded ranges had been greatly eroded, now hide from view several miles of the deformed terranes. Tertiary basaltic lava flows also effectively

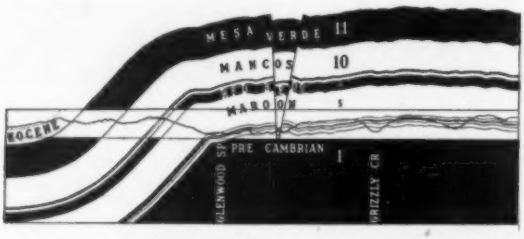


FIG. 11.—Glenwood Springs sheet (No. 13) and Grand Hogback sheet (No. 14), which covers the westernmost five miles of the section. Formations: (1) pre-Cambrian granite; (2) Sawatch; (3) Yule limestone and Parting quartzite; (4) Leadville limestone; (5) Weber and Maroon; (6) Red Beds; (7) Morrison; (8) Dakota; (9) and (10) Mancos; (11) Mesa Verde. Upturned Eocene beds (mostly Wasatch) on west margin of Grand Hogback sheet.

conceal the folded structures at a number of places in the section. Of these difficulties the basaltic lava covers are the least formidable, owing to their lesser area and more patchy pattern, which makes it possible in many places to infer the concealed structure from nearby outcrops of the folded beds. But the combination of these adverse conditions makes the Colorado Rocky Mountain section far less satisfactory than that of the Appalachians.

The entire cross-section of 135 miles was plotted on a scale of $\frac{1}{31680}$ on sheets of co-ordinate paper 20 inches in length, thus making each sheet cover 10 miles of section. Thirteen and a half sheets thus compose the plotted section. But in computing the amount of crustal shortening and the thickness of deformed shell, the most easterly 3 miles of the section were excluded from con-

sideration because they are truly a part of the plains and do not properly belong to the folded belt. The truly folded section is thus reduced to 132 miles in length (Figs. 5–11).

THE SHORTENING OF THE CRUST

Folding of strata under horizontal compressive stress is necessarily accompanied by a horizontal shortening of the deformed portion of the earth shell. The compressed mass is shortened in at least one of its horizontal dimensions, while it relieves itself by bulging upward in the direction of least resistance. The first objective in our problem is to determine the amount of horizontal crustal shortening which the Rocky Mountain region underwent while writhing in the throes of diastrophic revolution. The original length of the Lyons–Grand River section before folding may be determined with some approximation by measuring the total length of a selected layer through all the sinuous bends and wrinkles which are recorded on the plotted cross-section. A small corrective factor for the compacting of materials under the compression is to be introduced. The present horizontal length to which the section has been compressed is simply the map distance between the two ends of the section measured along the slight curve which was chosen so that the section shall cross the folds at right angles as explained on page 227. The difference between the length of the strata followed through all the folds and faults as reconstructed and the present map distance of the same section is the approximate shortening which the earth shell has suffered in being crumpled into mountains.

For measuring the length of the wrinkled strata all members of a thick series of sediments are not likely to be of equal value. In folds of the type technically known as similar, the individual beds have all been folded with the same curvature.[1] But in parallel folds, where the bedding surfaces are mutually parallel, the curvature of no two beds is exactly the same, and this difference in curvature implies the dying out of the folds in one direction or the other from a given bed. Hence an element of error is likely to be introduced in the hypothetical projection of younger beds over eroded

[1] C. K. Leith, *Structural Geology* (1913), pp. 106–7.

anticlines, or of older beds in the troughs of deep synclines. This error increases with the vertical distance from the observed stratum. It is clear therefore that cross-section measurements designed to give the crustal shortening should be made on stratigraphic horizons as near as practicable to those on which the field observations were actually made. The error of mechanical projection is then less serious.

Competent and incompetent beds also behave differently in folding. Various secondary adjustments between the different beds are, in many cases, accomplished by minor contortions and subordinate movements within the readily yielding incompetent layers, which, by accommodating themselves in buffer-like fashion to the major movements, facilitate the folding. The strong, competent layers, less subject to local irregularities, are likely to reveal truer estimates of the shortening of a region as a whole.

The ideal horizon for measurement should therefore have the following qualities: It should be stratigraphically near the beds on which the observations were actually made; it should be the top or bottom of a rather thin formation so as to limit variability; the formation should be resistant and hence predisposed to outcrop sharply in the field; it should be readily distinguished from other formations; and it should be so located in the column as to come to the surface at many places in the section. Such a formation in the Colorado Rockies is the Dakota sandstone. It is one of the most persistent and conspicuous of the formations, and it occupies the desired mean position in the stratigraphic column. The base of the Dakota sandstone was therefore adopted as the line to be measured in these studies.

On the cross-section sheets the base of the Dakota was followed through all the recorded folds and crenulations with a thin, flexible copper wire, which was bent so as to conform to every change of curvature. The wire was then straightened and compared with the scale for measurement. The difference between the length of the base of the Dakota, as thus measured along all the sinuosities of the section, and the present horizontal length of the section gives the amount of crustal shortening. Measuring each of the fourteen sheets separately gave the following results:

	Miles
No. 1. Lyons sheet (westernmost 7 miles)	
Length following base of Dakota sandstone	7.80
Present horizontal length	7.00
Shortening	.80
No. 2. St. Vrain sheet	
Length following base of Dakota sandstone	10.91
Present horizontal length	10.00
Shortening	.91
No. 3. Allen's Park sheet	
Length following base of Dakota sandstone	10.805
Present horizontal length	10.00
Shortening	.805
No. 4. Continental Divide sheet	
Length following base of Dakota sandstone	10.89
Present horizontal length	10.00
Shortening	.89
No. 5. Granby sheet	
Length following base of Dakota sandstone	11.085
Present horizontal length	10.00
Shortening	1.085
No. 6. Sulphur Springs sheet	
Length following base of Dakota sandstone	10.65
Present horizontal length	10.00
Shortening	.65
No. 7. Troublesome sheet	
Length following base of Dakota sandstone	10.45
Present horizontal length	10.00
Shortening	.45
No. 8. Gore Range sheet	
Length following base of Dakota sandstone	10.275
Present horizontal length	10.00
Shortening	.275
No. 9. State Bridge sheet	
Length following base of Dakota sandstone	10.635
Present horizontal length	10.00
Shortening	.635

	Miles
No. 10. Castle Peak sheet	
Length following base of Dakota sandstone	10.20
Present horizontal length	10.00
Shortening	.20
No. 11. Gypsum sheet	
Length following base of Dakota sandstone	10.235
Present horizontal length	10.00
Shortening	.235
No. 12. Dotsero sheet	
Length following base of Dakota sandstone	10.29
Present horizontal length	10.00
Shortening	.29
No. 13. Glenwood Springs sheet	
Length following base of Dakota sandstone	10.265
Present horizontal length	10.00
Shortening	.256
No. 14. Grand Hogback sheet	
Length following base of Dakota sandstone	6.20
Present horizontal length	5.00
Shortening	1.20
Summation: Entire Lyons–Glenwood Springs section	
Total original length (base of Dakota sandstone)	140.69
Present horizontal length	132.00
Total shortening	8.69

According to these measurements, the lateral thrusting which produced the Colorado Rockies compressed 140.69 miles of country into 132 miles, thus bringing two points on opposite sides of the folded belt 8 miles closer together than they were before the folding commenced. A crustal shortening of 8 miles distributed throughout a belt of originally 140 miles in breadth does not indicate very intense horizontal thrusting. The horizontal compression was much less than in the Pennsylvania Appalachians west of Harrisburg, where 81 miles were compressed into 66 miles, thus involving a shortening of 15 miles in this much narrower belt.[1] The

[1] *Jour. Geol.*, XVIII (1910), 235.

Colorado Rockies are therefore mountains in which the horizontally operating forces have achieved only moderate results. Farther north in Montana and Alberta, however, the great overthrust faults on the Rocky Mountain front imply that the horizontal thrusting has there been much greater.

THE ELEVATION OF THE FOLDED TRACT

When a region is folded by compressive stress, the horizontal shortening is compensated by vertical bulging, except in so far as there be an actual reduction in the volume of the material deformed. According to our fundamental postulate, if the amount of crustal shortening and the amount of the resulting vertical bulge be known, the thickness of the folded shell may be calculated. It is next in order to determine, if possible, the amount of vertical uplift which has resulted from the folding.

The first requisite for the determination of the amount of upswelling is a datum-plane above which the heights of the folds are to be measured. This datum-plane should coincide in position with the original surface of the region just before the folding commenced. The chief difficulty is to locate a datum-plane available today which will correspond in position to the original surface before folding. Mountains ideally built for such a study should be folded from a plain which was just at sea-level. A minimum of epeirogenic movement should accompany the orogenic disturbance. Then without the entrance of any other diastrophic changes to add complications, erosion should again reduce the folded tract completely to base level. This base level should correspond as closely as possible to the sea-level from which the mountains originally rose. This base level would then constitute the proper datum-plane above which to measure the heights of the folds.

The history of the Colorado region has been such as to render it rather well suited to a treatment of this sort. The closing stages of the Cretaceous period in Colorado witnessed a transition from the conditions of marine sedimentation to those of terrestrial deposition. Among the last beds laid down before the inauguration of the Laramide folding were vegetable accumulations which have since become coal. They were presumably formed in marshes

which were very close to sea-level. The Colorado sea-level at the close of the Cretaceous thus becomes the critical level. It was a plain approximately at sea-level which was arched and wrinkled into the Rocky Mountains by the diastrophic throes of the dying Mesozoic. Erosion by the rapid streams which sprang into being assailed the uplifted ranges and in time reduced them to the condition of a peneplain. But was, or was not, the level of this peneplain approximately the same as the level of the plain which earlier was folded into the mountains, and whose position today is such an important factor in our problem?

If it were known that the peneplain now visible in various portions of the Front Range had been developed at an elevation not greatly above sea-level, and that no changes of level had occurred in the interim between the period of folding and the development of this peneplain, then the latter could be accepted with confidence as the datum-plane, and it would be proper to measure the height of the projected folds above the present height of the peneplain. This of course presupposes that the orogenic folding movements were accompanied by little epeirogenic uplift. If, however, there was general regional uplift along with the folding this can be treated as subsequently indicated. But there were, in all probability, some changes of level during this very considerable period of time between the folding and the peneplain. A rise of the sea consequent upon the transfer of sediment from the uplifted lands to the ocean floor might confidently be expected. But at most this would amount only to a few hundred feet.[1] Furthermore it is to be noted that such a rise of the sea-level is in the nature of a return to the late Cretaceous conditions of widely transgressive seas, and hence toward the conditions and level from which the Rockies arose.

Far more to be feared are possible uplifts due to vertical forces operating independently of folding movements. There are two possibilities: A general regional uplift might have affected the entire area more or less uniformly; or the change in level might have been confined to local upbowings, either within

[1] R. D. George has estimated that the cutting away of the present continents and the deposition of the material in the ocean basins, would raise the sea-level about 650 feet. Chamberlin and Salisbury, *Geology*, I, 545.

the granite areas of the main ranges where it would readily escape notice, or within the areas of folded sedimentaries, portions of which might have been raised without materially increasing the intensity of the folding. But on the other hand renewed horizontal thrusting which merely carried further the folding process would cause no harm provided the thickness of the folded shell were the same as in the previous episode of folding. If the thickness were different, however, such later deformation would add a complicating factor. The folded Eocene volcanics at Windy Gap on the Grand River show that the folding cannot all be assigned to a single period, and this later folding may have been fully as intense in the region in question as the earlier Laramide diastrophism.

Although these are admittedly embarrassing factors which may have operated to some extent and which, if they did, lessen the accuracy of the final results, still it is believed that quantitatively they probably were not of sufficient magnitude to alter the general purport of the results. When it is noted that the average height of the folded tract throughout the entire section, according to measurements, is slightly over 13,000 feet above the datum-plane, it is apparent that a concealed, or unrecognized, uplift of 1,000 feet, or even 2,000 feet, will not change the order of magnitude or general significance of the results. The former would amount to but 7.7 per cent of the total; the latter to 15.4 per cent of the total. It is also frankly to be recognized that the method of projecting folds involves at best some error, and that when granite areas are included in the section the possible error becomes just so much greater. Such errors are inevitable owing to the limitations which the section imposes, and in the Colorado Rocky Mountain case they are considerable. Hence it is believed that refinements of method such as the introduction of corrective factors for the uplifting of the folded region during the interval between the folding and the peneplain stage, or for changes in the sea-level, or for the possible spreading and settling of the high standing mountainous masses, or for other changes, cease to be very vital in this case, though thoroughness in analysis requires their recognition. In any case they would be likely to offset one another more or less. The measure of inevitable error inherent in the section itself is so

considerable that it is scarcely worth while to attempt to evaluate these subordinate factors.

Recognizing the limitations of the method, but believing that the probable errors from these complicating factors are not great enough quantitatively to affect seriously the general conclusions, and that in any case they are probably less than the errors which will always stand in the way of a dynamic study of these ranges, owing to scarcity of data upon the granite areas, this investigation will proceed on the hypothesis that the peneplain level today represents with fair approximation the original level from which the folds arose. A hypothetical picture of this situation might be as follows: The folding of the Rockies was accompanied in all probability by some general uplift of the continent as a whole. Suppose that this uplift brought the Great Plains belt adjoining the Rockies to an elevation of 2,000 feet above the sea. Let us assume that the base-leveling process in developing the peneplain caused a rise of the sea to the extent of 500 feet. Then the peneplain, in order to constitute the correct datum-plane, should have been formed at an elevation of 1,500 feet above sea-level. Whether this imperfectly reduced Colorado peneplain, featured by many large monadnocks and nearly a thousand miles by the existent drainage routes from either the Gulf of Mexico or the Pacific Ocean, may reasonably have developed at this elevation is left to the reader to judge.

The average height of the reconstructed folded surface above this natural datum-plane was found to be as follows:

	Miles
No. 1. Lyons sheet (westernmost 7 miles)	1.51
No. 2. St. Vrain sheet	3.13
No. 3. Allen's Park sheet	3.90
No. 4. Continental Divide sheet	4.03
No. 5. Granby sheet	2.18
No. 6. Sulphur Springs sheet	1.68
No. 7. Troublesome sheet	2.42
No. 8. Gore Range sheet	2.40
No. 9. State Bridge sheet	2.24
No. 10. Castle Peak Sheet	1.62
No. 11. Gypsum sheet	1.98
No. 12. Dotsero sheet	2.54
No. 13. Glenwood Springs sheet	2.83
No. 14. Grand Hogback sheet	0.43

These figures should therefore represent, subject to the above-mentioned qualifications, the degree of uplifting which has resulted from the folding process.

It will be seen that in the matter of uplift the Grand Hogback sheet falls far short of all the others and appears to be in a class by itself. An inspection of the Grand Hogback section reveals the fact that, while the eastern half of the sheet shows moderate uplift, the western half, on the contrary, indicates subsidence, for the upper surface of the Cretaceous there dips more than 5,000 feet below the datum-plane. Only Tertiary rocks are exposed at the surface in the western portion, and in fact the geological map of Colorado shows that these Tertiary rocks continue to the southwest without interruption for fully 50 miles more—even to within 20 miles of Grand Junction. This area west of the Grand Hogback constitutes the southeast portion of the extensive Uinta Basin, which is a structural basin filled with thick Eocene deposits. Throughout this basin of heavy Eocene sedimentation the upper surface of the Cretaceous has been depressed below our datum-plane.

The Grand Hogback is a sharp ridge of upturned resistant strata, which marks the location of a sharp monoclinal flexure between the uplifted Rocky Mountain region on the east and the downwarped Uinta Basin to the west. A study of the Grand Hogback cross-section sheet raises the question whether subsidence of this basin of Eocene sedimentation may not have been as important in developing the Grand Hogback monoclinal flexure, as upwarping on the Rocky Mountain side. But whether subsidence or uplift has been the more effective in bending the strata, the earlier Eocene beds in any case exhibit essentially as much folding as the underlying Cretaceous, indicating that the flexing for the most part has come after the Laramide disturbance. Later studies may show whether or not this bending was synchronous with the episode of folding which affected the Middle Park beds near Windy Gap. Because the extent of the subsidence suffered by the Uinta basin interferes with any reliable determination of uplifting on its borders, the Grand Hogback sheet will not be included in the section used for estimating the thickness of the folded Rocky Mountain

shell. The measured section will thus end with the western edge of the Glenwood Springs sheet, 1¼ miles southwest of Glenwood Springs.

Since the country was corrugated into the lofty folds portrayed by the reconstructed cross-section, the high-standing areas have been subject to some relaxational movement. Portions of the area have settled by the process of normal faulting. It is to be noted that all the faults shown in the cross-section are located on the limbs of anticlines or in the plateau-like region between State Bridge and Glenwood Springs. The faults appear to shun the synclinal troughs. This would imply a spreading of the anticlinal arches accompanied by downslipping on the sloping flanks. That more of these normal faults are located on the western limbs of anticlines than on the eastern may have been a chance matter of local conditions and so of little import, or may possibly point toward a westward creep in the relaxational process. There are several theoretical reasons why the latter might be looked for, but the evidence is so meager as to merely raise the query. Since the settling along these faults took place presumably after the folds had attained their growth, the foregoing estimates of the height of the folded tract have been made on the basis of the original folds.

THE THICKNESS OF THE FOLDED SHELL

Having estimated the crustal shortening and the vertical bulging which have arisen from the folding, the depth of the folded zone is to be calculated. According to our formula, the product of the present horizontal length of the folded section times the vertical uplift equals the product of the shortening times the depth of the folded shell (Fig. 12). This is true except in so far as there has been an actual change in volume due to the compacting of materials under the comprehensive stresses. As discussed in a previous paper,[1] the amount of shortening due to the mashing of the strata and the compacting of materials during folding is relatively small in comparison to that resulting from corrugation—in all probability not more than 5 per cent. Furthermore, the shortening due to the compacting of the rocks is more or less offset by subsequent elongation of the strata arising from jointing, from the opening of fissures, and the penetration of igneous intrusions.

[1] *Jour. Geol.*, XVIII (1910), 236–37.

But as any corrections for these qualifying factors on the basis of present information would be essentially arbitrary, they will be passed over for the present. Corrections to cover them can, however, be introduced at any subsequent time if the necessary information should become available, or if it should be felt that these factors are of sufficient quantitative importance to justify their further consideration.

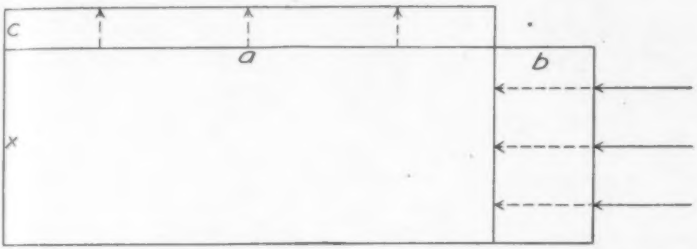


FIG. 12.—Diagram to illustrate the method of calculating the depth of a folded block.

a = the present horizontal length of the section
b = the shortening caused by the folding
c = the upbowing resulting from the folding
x = the depth of the deformed block

Then $(a+b)x = a(x+c)$

$$ax+bx = ax+ac$$

$$x = \frac{ac}{b}$$

Using the method above outlined, the thickness of folded shell was calculated separately for each ten-mile sheet of the Lyons–Grand River section. The results were as follows:

	Miles
No. 1. Lyons sheet (westernmost 7 miles)	13
No. 2. St. Vrain sheet	34
No. 3. Allen's Park sheet	48
No. 4. Continental Divide sheet	45
No. 5. Granby sheet	20
No. 6. Sulphur Springs sheet	26
No. 7. Troublesome sheet	54
No. 8. Gore Range sheet	87
No. 9. State Bridge sheet	35
No. 10. Castle Peak sheet	81
No. 11. Gypsum sheet	84
No. 12. Dotsero sheet	88
No. 13. Glenwood Springs sheet	107

The results are presented diagrammatically in Fig. 13, in which each section has been represented as though it were an isolated rectangular block, no attempt being made to accommodate these blocks to one another as was done undoubtedly in the real case.

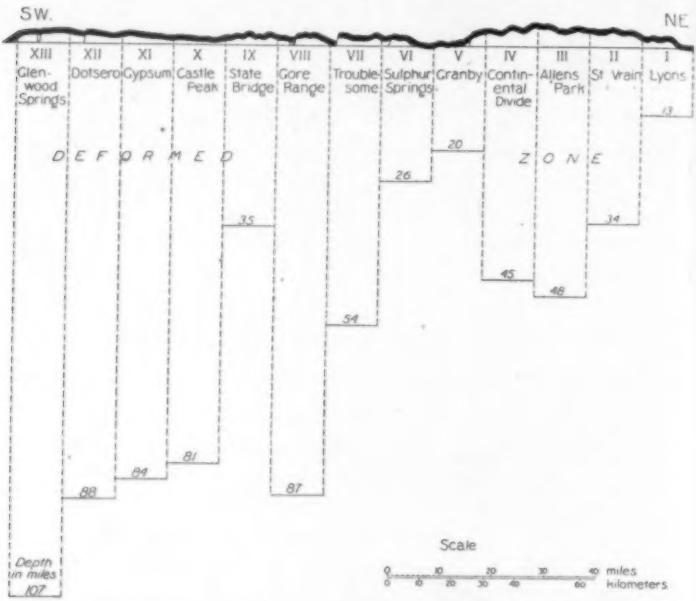


FIG. 13.—Diagrammatic cross-section of the deformed zone for this portion of the Colorado Rockies. The thirteen separate blocks are numbered in order from northeast to southwest. The heavy black line gives a restoration of the Laramie and Mesa Verde formations and thus represents the original folded surface. The depth in miles is given at the bottom of each block. No attempt is made to bound the deformed zone by a curved lower surface, as was presumably the actual case in the field.

Curved boundary lines would certainly conform more closely to nature, but nothing more than the strictly diagrammatic block-outline is ventured here.

Fig. 13 appears to show that beneath the two principal granite ranges, which today mark the lines of greatest upfolding, the disturbed zone reached deeper levels than on the immediate

flanks of the upfolded belts. The granite mountain belts are more deeply rooted than the less uplifted strips adjacent. They constitute the true Rocky Mountains of this latitude.

According to the testimony of the Lyons sheet the folded shell of the Front Range thins rapidly as it approaches the Great Plains. This repeats in type, though less strikingly, the rise of the boundary shearing plane on the western border of the Appalachian Mountains near Tyrone, Pennsylvania.[1] Neither the Lyons section nor the Tyrone section developed an actual fracture, though they suggest an approach to it. But on the western border of the Appalachians farther south the boundary shearing plane has actually emerged from the depths as a strong thrust fault which separates the disturbed mountainous belt on the east from the region of horizontal strata on the west. This is especially conspicuous in Tennessee. In close analogy to this, in Montana and Alberta, the Rockies are separated from the Great Plains by an overthrust fault, or faults, of great displacement. These instances pointedly suggest the generalization that bordering thrust faults, particularly on the inland margin of a strongly deformed mountain belt away from the assumed active oceanic segment, are a common, and if so significant, phenomenon, especially as they accord with the theory of mechanics. With greater intensity of thrusting and the appropriate rock materials, the great upfold in the foothill belt of the Colorado Rockies would presumably have passed into a bordering thrust fault.[2] Such a bordering thrust fault appears to have developed on the east flank of the Wet Mountains, where that range continues the Rocky Front *en échelon*, south of the Arkansas River.[3] The pre-Cambrian granite has been thrust eastward over the Cretaceous strata of the plains and lower foothills, and also in one place over a conglomerate which has been classed tentatively as Arapahoe.

The westernmost four divisions of the plotted section, representing the region of but slightly disturbed strata between State

[1] *Jour. Geol.*, XVIII (1910), 245, Fig. 6.

[2] Some local fracturing did develop at Boulder and at Golden. See Ziegler, *Jour. Geol.*, XXV (1917), 728–40.

[3] C. W. Washburne, "The Canon City Coal Field, Colorado," *U.S. Geol. Surv., Bull. 381* (1910), p. 342 and Pl. XVIII.

Bridge and the Grand Hogback, constitute in reality a plateau region rather than a folded mountain area. This strip is to be considered the southeastern extension of what has been called the White River plateau. In fact the deformation in the westernmost forty miles of the chosen section was so slight that this strip was not originally included in the folded mountain section measured in 1915. It was added in 1916. Fig. 13 indicates that beneath this region of plateau-like uplift the lateral thrusting movement has been distributed through a thick zone which has been deformed only slightly.

To interpret Fig. 13 the deforming movement pictured as the result of thrusting from the west was distributed at first through a thick shell in the plateau region, but in this thick zone it reached only a low degree of intensity. The region was in consequence but feebly wrinkled. But in the region next east, where the Grand River today turns abruptly northwestward near State Bridge, the activity was concentrated in a thinner movable zone which was far more sharply folded. This marks the western flank of the folded belt which culminated in the Gore or Park Range. Next east of this, less folding in the middle of the Gore Range indicates greater depth of shell there, followed by thinning again on the eastern flank of the Gore Range. The disturbed mass became thinner again in the Middle Park region, where the uplifting was relatively less, and then it deepened rapidly beneath the Front Range, where the uplift was greater, again thinning out rapidly to the edge of the Great Plains, which border the folded belt on the east. In this way the Front Range repeated the wedge-shaped block of the Park Range.

These results are based on the assumption that the shortening has remained the same throughout the full depth of each deformed block. If the shortening, in reality, increases with depth these figures are overestimates of the thickness of the folded shell. But on the other hand, if it be true that there was less folding and less shortening in the deeper portions of these blocks, these figures are underestimates of the depths to which the folding extended. Of the two alternatives the latter seems the more probable. With increasing depth below the surface, the resistance of the rocks to

deformation steadily increases, thus necessitating greater and greater stress differences in order to cause folding. Unless the stress differences increase as rapidly as does the resistance with increasing depth below the surface, folding, instead of becoming easier in the deeper levels as the time-honored doctrines have taught, becomes more and more difficult and hence less effective.[1] Daly has called attention to the fact that in the Selkirk Range of British Columbia the Shuswap terrane of presumable Archean age has escaped much of the folding which so powerfully affected the younger rock systems. The basement rocks show comparatively slight deformation, from which Daly concluded that "the earth shell engaged in the post-Shuswap orogeny was only a few miles, perhaps 6 or 8 miles, in depth. Over the Shuswap terrane this shell was thrust and crumpled."[2]

Beneath the surface the sharpness of folding probably at first increases down to a level of greatest folding, below which it again diminishes. With increasing depth below the level of sharpest folding, the folds of the wrinkled shell may either die out gradually or the adjustment may be accomplished by shearing between the upper, more movable portion and the lower, less movable portion. Fig. 13 is based on the assumption of undiminished intensity of folding throughout the full depth of each deformed block, and hence calls for adjustment by shearing below. In the actual case the adjustment was probably accomplished, not by shearing alone, but by some combination of the two processes. But at present the relative importance of the two cannot be decided, except upon arbitrary assumptions. Too much weight must, therefore, not be given to the precise figures for the depth of the various blocks.

Estimates of the depth of deformed shell by this method are subject to modification for such uplifts as were not occasioned by the horizontal compression. In this section of the Colorado Rockies it is quite possible that upbowing has recurred along the

[1] F. D. Adams and J. A. Bancroft, "On the Amount of Internal Friction Developed in Rocks during Deformation and on the Relative Plasticity of Different Types of Rocks," *Jour. Geol.*, XXV (1917), 597–637.

[2] Reginald A. Daly, "A Geological Reconnaissance between Golden and Kamloops, B.C., along the Canadian Pacific Railway," *Geol. Survey of Canada, Mem. 68* (1915), pp. 53–55.

old lines of yielding during the critical interval between the folding of the mountains and the establishment of the peneplain, and any such vertical movement whose occurrence and extent have not been detected and duly covered by a correction, would reduce the accuracy of the calculated results. But on the other hand, any uplifts subsequent to the development of the peneplain do not in any way enter into the problem, for the adopted method of treatment eliminates their influence. The testimony of folded mountain ranges in general is to the effect that later episodes of yielding commonly follow along the lines of earlier folding, doubtless because they have become the lines of least resistance. These later episodes of diastrophism may obviously be either further folding under compressive stress or uplifts with but little folding. The effect of the latter possibility in the case under discussion would be to increase the height of the folded section, without correspondingly adding to the measured shortening, and thus make the calculated depths of the Gore Range block and Front Range block too great. The other alternative of further folding along the old lines is less serious, for, as has been stated before, the outcome of the computations will be the same whether the folding all took place at one time or at different times, provided the same thickness of shell was affected each time. If two or more episodes of folding deformed different thicknesses of shell, the computed depth resulting from the adopted method of treatment would be in the nature of an average. In this connection it is of significance to note the statement of Hills that the post-Bridger folding was essentially a continuation of the post-Laramie folding, for the second movement began where the first terminated, and if the post-Laramie movement had been further continued the resulting structure might ultimately have been the same.[1]

In contrast to uplifting, any subsidence of intermontane basins of deposition, or local downwarping, during the critical interval between the mountain folding and the development of the peneplain would tend to offset the bulging effect of the folding process, and thus lead to a too low estimate of the height of the folded tract. This in turn would result in giving an underestimate of

[1] R. C. Hills, "Orographic and Structural Features of Rocky Mountain Geology," *Proc. Colo. Sci. Soc.*, III (1888–90), 419.

the depth of the folded block. In certain portions of the Granby, Sulphur Springs, and Troublesome areas, beds of Uinta age occupy several basins below the peneplain level. The position of these beds strongly suggests a sinking of these basins under the accumulation of early Tertiary times. Though the extent of the settling probably was not great, still it may have been sufficient to cause the calculations to assign a somewhat too meager depth to the rather shallow Granby and Sulphur Springs blocks.

In the foregoing computations only the crustal shortening at right angles to the trend of the ranges has been considered. But folds are properly considered in three dimensions, and some longitudinal warping and pitching of the folds is to be expected. Longitudinal warping would involve crustal shortening in a direction parallel to the trend of the range and at right angles to the shortening above considered. The folds measured in the Lyons–Grand River section exhibit pitching in some places, but this did not appear sufficiently pronounced to justify the extra field work necessary to measure the northwest-southeast warping for the different sections. The warping at right angles to the main folding was most apparent in the State Bridge and Glenwood Springs sheets. This minor warping, like the major folding, causes upswelling of the folded tract. Hence in practice the effect of ignoring the minor warping in the direction of the ranges is to assign all the observed upswelling to the work of the major folding and thus obtain an overestimate of the depth of the folded zone.

There are therefore certain subsidiary considerations, such as uncorrected uplifts subsequent to the folding, and the neglect of upswelling from longitudinal warping whose influence is to cause overestimates of the depth of folded shell. But over against these is the uncorrected sinking of certain areas of Eocene sedimentation, and the assumption of uniform shortening throughout the full thickness of each deformed block, whose probable influence is to cause underestimates of the depth. In all probability each of these is the source of some error. How nearly they offset each other and so cancel out of the equation cannot be told at present. But they probably do not greatly modify the general order of magnitude of the calculated results.

GENERAL DISCUSSION AND CONCLUSIONS

These studies would seem to show that the Colorado Rockies differ in several notable respects from the folded Appalachians of Pennsylvania.

1. They have suffered, in the first place, much less horizontal compression. From the Great Plains to the Uinta Basin, 140 miles of country were compressed into 132 miles, thus involving a shortening of only 8 miles, while west of Harrisburg alone 81 miles of strata were squeezed into 66 miles of present Appalachians, which means a shortening of 15 miles in this much narrower belt. This does not include the folding in the metamorphic belt east of Harrisburg.

2. A much thicker shell seems to have been involved in the Rocky Mountain diastrophism than was actively deformed in the Appalachian folding. The apex of the Pennsylvania Appalachian wedge was but 32 miles below the surface, while the roots of the Gore Range reached a depth of 87 miles and the plateau tract near Glenwood Springs had a depth of 107 miles.

3. Vertical lifting and plateau-forming movements have been more pronounced in the Rockies than in the Appalachians. This is indicated both by the outcome of this analysis, and also by the present high altitude of the Colorado Front Range peneplain, though the elevation of the latter, to be sure, came long after the principal folding, which is the basis of this investigation.

4. The formation of the Colorado Rockies was accompanied by much more vulcanism than the formation of the Appalachians.

These conclusions lead naturally onward to certain additional deductions and further applications. These specific results confirm the principle that there is an inherent relation between thickness of shell actively involved and intensity of deformation. This justifies the conclusion that mountain ranges displaying intense folding, thrust faulting, and dynamic metamorphism resulting from extreme horizontal compression are associated with a thin, shallow shell. This thin, movable shell, which has been greatly folded and faulted, shears upon the less yielding base beneath it. Ranges of this sort are the Appalachians and presumably the Jura, Alps, Scottish Highlands, Scandinavian chain, and others of great short-

ening and intense horizontal thrusting. If the active crumpling in a range like the Alps were not confined to a very thin shell the resulting vertical bulge would be stupendous.

Those ranges in which a much thicker shell has yielded to the stresses are characterized by open, gentle folding, only moderate shortening, but more pronounced vertical lifting. The Colorado Rockies belong to this group. Moderate folding distributed through the thicker zone accomplishes the same amount of vertical bulging as greater shortening of a thinner zone. Shearing along a few well-defined planes may well be a less important means of adjustment beneath the thicker deformed zone than beneath the thinner one. Adjustment in the thicker zone is probably due to gradual accommodation by the slow dying out of folds below, with perhaps more or less local, distributive shearing. Upward yielding in the direction of least resistance being relatively more conspicuous than horizontal movement when a thick shell is deformed, this type of mountain building crowds closely on the borders of the plateau-forming type of diastrophism. The western portion of the Lyons–Grand River section, from State Bridge to the Grand Hogback, where the disturbed zone had a thickness rising from 81 to 107 miles, portrays what was essentially a plateau uplift, and suggests the actual merging of this mountain type into the plateau type.

An incidental feature of some significance is the bordering thrust fault observed in several instances on the inland margin of a strongly deformed mountain belt farthest removed from the oceanic segment from which the thrusting presumably has come.

Since the Laramide disturbance the Colorado Rocky Mountain region has been the scene of much vulcanism. The products of this, in places, have obscured the folded strata beneath, and thus have added materially to the difficulty of making an accurate cross-section of the mountainous belt. In general, Tertiary vulcanism has been a prevailing phenomenon throughout the Rockies from Montana to New Mexico. In the region of the present Appalachian Mountains, on the other hand, there has been very little vulcanism. There were the Upper Triassic lavas of the Newark series, to be sure, but they were east of the present mountains and,

breaking out long after the Appalachian folding, they appear to be genetically related to faulting nearer the coast in a diastrophic movement which occurred toward the close of the Triassic. Lavas and tuffs caused no trouble in measuring the Pennsylvania mountainous section.

In view of the fact that the Pennsylvania Appalachians, which show less volcanic activity, have resulted from the crumpling of a comparatively thin surface shell, while the Colorado Rockies, with more extensive vulcanism, involved a thicker shell, it is suggested that there probably is a genetic relation between the depth to which the roots of a mountain range extend and the amount of vulcanism associated with it. It seems very rational a priori that if the zone disturbed in the formation of a folded range does not extend far below the surface, it would not be likely to lead to the generation of magmas nor greatly facilitate their escape if already present in the undisturbed depths below, even though the folded zone itself may be intensely deformed and shear strongly over the underlying base. But if, on the other hand, the disturbed zone reaches down to considerably greater depths, even though the deformation itself be not so intense, it may readily afford better opportunities for the generation or the rise of magma to the surface. At many points the difference in depth of disturbance may be sufficient to decide between a rise of magma and no upward movement of the magma, or by operating through relief of pressure, perhaps decide between potential magma and actual magma.

On theoretical grounds the thin-shell mountains should be accompanied in their growth by relatively little vulcanism, while the growth of thick-shell mountains should be attended by relatively greater outpourings of lava. Looking over the mountain systems of the globe one might select, as some of the conspicuous illustrations of sharp folding, great thrust faulting, and much crustal shortening, the Alps, the Scandinavian chain, the Scottish Highlands, the Backbone Range of Brazil, and perhaps the Rocky Mountains of Alberta. These would seem to be mountains of the thin-shell type as nearly as can be judged without actual measurements upon them. In each of these cases it will be observed that only moderate igneous activity was associated with the mountain

building. This seems perhaps the more remarkable when it is considered that any great disturbance of the outer portion of the earth is likely to stimulate outward movements of liquid magmas, and in some cases through relief of pressure actually to cause liquefaction and the development of magmas.

As representatives of the thicker-shell type of mountains in which vertical movements are more pronounced, and horizontal thrusting and shortening less conspicuous, one might select in addition to the Colorado Rockies, the Cascades on the Pacific Coast,[1] the great chains of Andes, particularly the Western Andes, and the Abyssinian Mountains. The extravasation of vast floods of lava marked the growth of these ranges. In the light of this inquiry, it may be inferred that these mountains had deeper roots than the more sharply folded ranges, and that this greater depth of disturbance was an important factor in causing the greater igneous outbursts.

In final summation it may be remarked that within Colorado the Rocky Mountain system is characterized by open, gentle folding, moderate crustal shortening affecting a zone several scores of miles in depth in its deeper portions, by strong uplifting, and by the extrusion of much lava. Extending the range of view, it is to be noted that this dominantly vertical diastrophism with its ample outpourings of lava is typical of much of the western United States. On the other hand, in northwesternmost Montana and throughout Alberta, the ranges of the Rocky Mountain system exhibit low angle thrust faulting on a grand scale, greater crustal shortening which presumably has affected a thinner surface shell, and has been accompanied by less volcanic activity. It thus appears that a single mountain system of great length may develop both types of deformation in different portions of its extent.

[1] See Bailey Willis, "Physiography and Deformation of the Wenatchee-Chelan District, Cascade Range," *U. S. Geol. Surv., Prof. Paper 19* (1903), pp. 95–97.

NOTES ON PRINCIPLES OF OIL ACCUMULATION[1]

ALEX. W. McCOY
Empire Gas and Fuel Company, Bartlesville, Oklahoma

Petroleum deposits of commercial importance occur in sedimentary rocks. The great majority of such deposits in the mid-continent field are found in sands or in thin-bedded porous limestones with intervening shales. These shales are generally dark colored, often black, and carry bands of highly bituminous material. Paying amounts of oil have not been found in very thick sandstones or limestones without notable shale "breaks,"[2] or without being closely associated with shale horizons. Even the Bartlesville, the thickest pay sand of the region, shows many black shale partings when the cuttings of each screw are examined carefully.

The examination of a number of such cuttings in the proximity of many different oil sands throughout the mid-continent field reveals the fact that black bituminous shales are invariably present.[3] These beds are often described by the drillers as coal, asphalt, or black lime, according to the hardness and appearance of the material. The shales are typical oil shales, quite similar in character to those of Colorado and Utah. The bituminous material occurs in solid form as none of the ordinary solvents show coloration after solution tests. Upon distillation, such shales have given off petroleum-hydrocarbons. The sands are entirely barren of such compounds.

Before concentrations of petroleum can take place, it is necessary that this solid organic gum called kerogen be changed so that liquid hydrocarbons are formed. Such a change has com-

[1] Published through courtesy of the Empire Gas and Fuel Company.

[2] Drillers are accustomed to speak of thin changes in a thick formation as "breaks."

[3] In cuttings examined to date the one exception to this statement is the Hoy (1,100 feet) sand of the Garber, Oklahoma, field.

monly been made in the laboratory by heating. However, the majority of oil deposits are located in the upper 3,000 feet of sediment, and evidence that the necessary distillation temperature of 450° F. has ever been reached at such places is quite lacking. Oil-field waters of this region are seldom above 100° F. in temperature, ranging generally from 80 to 90° F. Consequently it is difficult to explain the reduction of liquid oil from bituminous shales by heat, except possibly in very limited local areas of intense friction. Even in such cases the amount of heat is highly problematical.

The other most important factor below the surface of the earth is pressure. Pressure alone can cause no change in this material when the included water is not allowed to escape, and the shales are only compacted when the water is given free passage.

These facts led to a laboratory investigation of rock flowage upon the hypothesis that the mechanical energy or work done upon the shale by applying a force through a distance would accomplish the same results as the equivalent amount of heat energy. The experiment was carried out by Mr. E. A. Trager and the author, similar to the experiments of Adams and Bancroft.[1]

1. *Description of flowage experiment.*—Cylindrical steel bars (Fig. 1) were sawed in lengths of about 3 inches and bored into tubes having an inside diameter of 2 cm. The thickness of the walls in the center of the cylinders was reduced to 0.25 cm. Pistons of steel were turned to fit the tubes. Cylindrical pieces of an oil shale (yielding 25 gallons per ton and having a crushing strength of about 3,000 pounds per square inch) were cut into 1-inch lengths and placed in the center of the tubes, where the thickness of the walls was reduced. The pistons were then inserted on either side of the shale cylinder and pressure was applied to them in a Riehle compression machine, thus squeezing the shale and eventually bulging the tubes in the center. By so doing, the shale was made to flow. No appreciable amount of heat was was developed. Solution tests taken before the experiment gave no indication of liquid hydrocarbons, while those taken after flowage with the same shale gave strong coloration. In some cases, after the experiment small globules of oil could be seen in the shale with a hand lens. The steel tubes necessitated

[1] Adams and Bancroft, "On the Amount of Internal Friction Developed in Rocks during Deformation and on the Relative Plasticity of Different Types of Rocks," *Jour. Geol.*, XXV, 597.

such a great pressure to make the bulging that tubes of brass and softer metals were tried. The results were substantially the same. Details of this work will be described in some later paper.[1]

The experiment is referred to here in order to show how liquid hydrocarbons may be formed in the shales from the solid bituminous material at ordinary temperatures and under pressures of 5,000 to 6,000 pounds, such as exist at the depth of oil-bearing horizons; and that the only places where such compounds would be formed are in areas of differential movement.

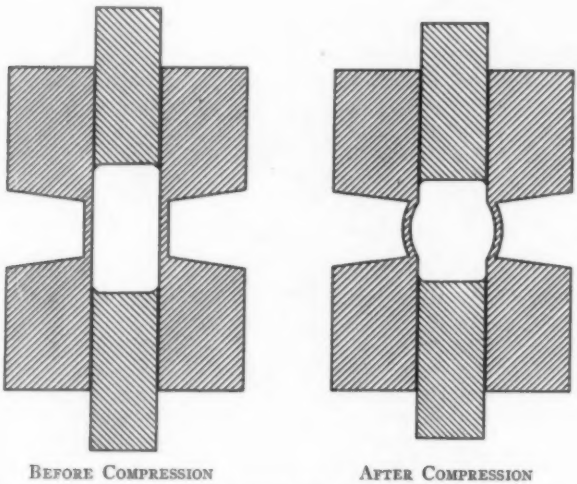


FIG. 1.—Longitudinal section through steel cylinder inclosing rock column

After the oil is once formed in the shales, it is collected in the porous zones by water. The action is one commonly called "Capillary Concentration."[2] Water, having a greater surface tension and adhesion for shale particles than oil, moves into the smaller openings of the shale, and the oil is thus forced into the larger openings of the porous water horizons. Before this can take place, the water sand or reservoir rock must come in direct

[1] Unpublished manuscript of E. A. Trager and the author.

[2] C. W. Washburne, *American Institute Mining Engineers*, 1914, p. 830.

contact with the oil-soaked shale. Oil shales are usually separated from sand or porous rock by barren shales. These overlying and underlying a water stratum would be saturated with capillary water, and it would be impossible for oil to migrate through even a very thin water shale, for reasons stated later. It then becomes necessary for breaks in the intervening shale to occur so that the water may come in direct contact with the oil-soaked horizon. Such conditions can be brought about only by faulting or jointing. A very small displacement or a slight open joint may give the water from large openings a chance to

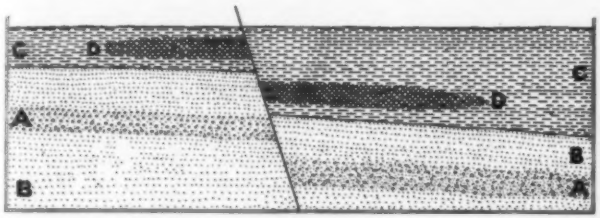


FIG. 2.—Diagram of apparatus for accumulation experiment before partition was removed, showing oil in shale marked "D."

enter the oil-soaked shale and the oil to exchange places with the water. To substantially back these statements, the following experiment is offered:

2. *Description of accumulation experiment.*—A water-soaked sand bed (*B*) two inches thick was placed in a glass box 18 in. by 6 in. by 6 in. (Fig. 2). In the center of the box a celluloid sheet partition was set at a slight angle to the vertical and effectively sealed to the sides and bottom of the box with putty. Each division of the box was then water-tight. The sand bed was built higher on one side of the partition than on the other; the beds on each side of the partition were slightly sloping in the same direction, representing a normal fault. About one inch below the top of the sand bed was a thin layer of coarser sand (*A*) running uniformly throughout. Water-soaked mud (*C*) from ground shale (passing a 200-mesh sieve) was placed above the sand. This layer was about one inch thick. Then a one-inch layer of oil-soaked mud (*D*) was built over the area adjoining the celluloid partition, but not extending to the corners of the box. The reason for not covering the entire area with oil-soaked shale was to avoid the fittings around the corners as a perfect seal is hard to accomplish in corners of such a small box. The

remainder of the box was filled with water shale. Each formation had the corresponding displacement on either side of the partition. The box was allowed to stand for twenty-four hours. No movement of the oil was noticeable after that time. The celluloid partition was then carefully pulled out so that the beds were undisturbed and the softer beds of the shale immediately closed the small opening left by the removal of the sheet. Within one hour from this time oil began to collect in the porous layer of the sand. This continued for several hours until the porous sand was nearly filled on each

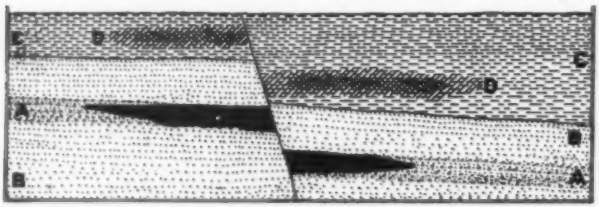


FIG. 3.—Diagram of apparatus for accumulation experiment after partition was removed, showing oil partially replaced from "D" and accumulated in "A."

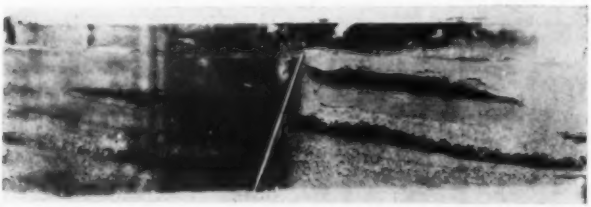


FIG. 4.—Photograph of apparatus used in Experiment 2, showing the accumulation of oil in the sand.

side of the represented fault (Fig. 3). Capillary water partially had replaced the oil in the original oil-soaked shale and had sealed the remaining oil completely in the center of the shale body. After the oil had come to an equilibrium in the sand, it did not move apparently up the dip but remained in the porous zone surrounded by water. The relative position of oil and water was stationary until the experiment was torn down two weeks later. Note photograph shown in Fig. 4.

The foregoing evidence shows that liquid petroleum in shale cannot move into the porous water horizons until the intervening

barren shales are opened by joints or the oil shale layer faulted against water strata.[1]

Capillary action is very slightly increased with the increase of pressure,[2] consequently the movements underground are not materially different from those in the laboratory. The action, however, varies with the absolute temperature of the liquids, but in the upper 5,000 feet of sediment the temperatures would not alter the actions as described.

When the oil once reaches the sand or porous zone, it adjusts itself to occupy the larger openings and remains there indefinitely unless disturbed by some outside factor.

It is impossible for oil to migrate any great distance in the oil-bearing formations of the mid-continent field. A discussion of this point is taken up in three parts: (1) difficulty of migration from the mechanical standpoint; (2) negative experimental evidence; (3) evidence of lenticular character of water zones.

The movement of oil in water-soaked sediments is almost entirely a problem of surface tension. Water, having a greater surface tension and attraction for rock surfaces than oil, moves into the smaller pores occupied by the oil and forces it into larger openings. Such movement is characteristic as long as the openings are less than 0.1 mm. Where the sand grains are unusually large (3 mm. in diameter or over) or where induced openings have been made locally in some hard formation, sorting due to specific gravity is free to take place if the unbalanced weight overcomes the friction of the movement.

Relative forces thus affecting oil movement can be figured from the size of the openings in the rocks.[3] In a shale at a depth of 1,500 feet, where openings are 0.01 micron, the capillary force

[1] It is the popular belief that faults are detrimental to oil accumulation since they afford passages for upward migration of oil, thereby allowing the oil to escape. Such may be the case occasionally where the formations stand open along the fault plane for hundreds of feet. In the oil fields of Oklahoma most faults probably never reach the surface. Shales being so predominant in the section invariably fall together along the fault plane, thus tightly sealing the majority of faults so that they are not generally conductors of oil upward.

[2] Johnston and Adams, *Jour. Geol.*, XXII, 9.

[3] *Ibid.*, p. 13.

of the water to replace the oil is about 1,400 lbs. per square inch;[1] the unbalanced force due to specific gravity is less than 0.1 lb. per inch; and frictional resistance is probably a fraction of a pound per square inch. As the openings become larger the capillary-expelling force of the water becomes less and when these have reached 0.5 mm. this force is zero. Then the unbalanced specific gravity and fractional resistance are the only forces to be accounted for. Such places are only local in the sedimentary series, and the great majority of openings in oil-bearing formations are much smaller. The force necessary to make oil migrate through a wet shale (openings 0.01 micron) for a depth of 1,500 feet is about 4,000 lbs. per square inch. This is about 1,500 lbs. per square inch greater than the combined rock and complete hydrostatic pressure. Consequently, it is utterly useless to assume migration of oil through wet shale. Even when the openings in a sandstone are as much as 0.1 mm. in diameter, the capillary resistive power is about 0.4 lb. per square inch compared with 0.1 lb. per inch, the unbalanced force due to specific gravity. The instant an oil particle (migrating in water sediments) reaches a series of openings larger than those surrounding it, it stops and remains there indefinitely, as long as these surrounding openings are less than 0.1 mm. All sandstones are irregular and a series of openings larger than 0.1 mm. is never very extensive.

3. *Experiment on migration of oil in wet sand.*—A water-soaked (20-mesh) sand bed with a 20° slope was placed in a glass box 18 in. by 6 in. by 6 in. (Fig. 5). Near the lower end of the stratum a small volume of larger (10-mesh) sand grains was filled with oil and covered with water-soaked shale. This was allowed to remain for one week and no movement of the oil had taken place. Then glass tubes were inserted into the sand at either end of the box. Water was pumped out of tube No. 1 at the higher end of the sand bed and at the same time water was allowed to run into tube No. 2 at the lower end. This was continued until the amount of water forced through the sand was several times its volume. No movement of the oil resulted. The accompanying photograph, Fig. 6, was taken after the experiment.

[1] These figures are rough approximations from data of Johnston and Adams (*ibid.*); also Harkins, Davies, and Clark, *Journal American Chemical Society*, XXXIX, No. 4 (April, 1917), 531.

This experiment is cited to show that oil does not migrate up the dip due to specific gravity differences, nor is it forced upward by circulating water.

On the outcrop the sands in the oil-bearing formations are not continuous but lenticular. By careful study of sands from well logs in different pools of the mid-continent field, the lenticular property of the sands becomes more evident. Water analyses

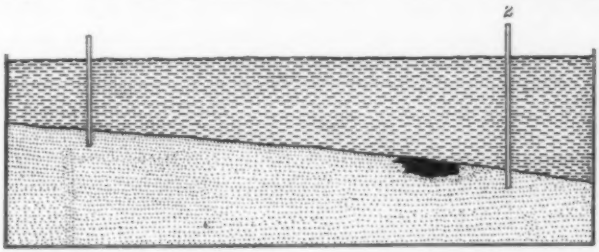


FIG. 5.—Diagram of apparatus for experiment showing no movement of oil in sand

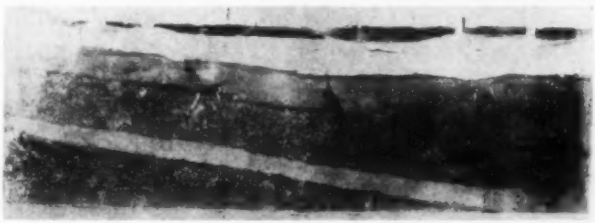


FIG. 6.—Photograph of apparatus used in Experiment 3, showing the oil remaining in the sand where it was originally placed.

also corroborate this fact. Results from four hundred water analyses to date point to the fact that each sand lens carries a definite water, uniform throughout and differing in some respect from the water of another lens. These waters are probably connate sea waters uncontaminated by surface water. In nearly pure silica sands the water differs little from sea water. In limy members or where other soluble minerals are noted the water is much higher in total solids than sea water. The present work seems to indicate that the change from normal sea water can be accounted for

by the minerals in, and surrounding, the water horizon. If the water shows no connection between different lenses in a sedimentary series, surely continuous sands or porous zones cannot be expected and consequently the analyses check the impossibility of migration from one lens to the other.

The pressure on the oil as it exists in the porous stratum is the same as that on the water which previously occupied the space. A volume of water replaces approximately an equal amount of oil, consequently the pressure in the reservoir remains the same. When the relation of oil to advancing water is such that the oil may be trapped and forced forward by capillary water, considerable pressure may accumulate on the oil due entirely to the capillary action of the water. Such conditions would be local if ever present and of little importance in commercial oil pools.

Pressures on fluid in an oil sand are often spoken of as "rock pressure" or "gas pressure." Neither term exactly defines the accumulated pressure on the fluid. The maximum static pressure available in any porous zone is a function of the size of the openings around that stratum. The determining factor is the capillary resistance of the water in the adjoining small openings. This factor depends upon the character of the sediment and the amount of compactness of the same. As the beds are more deeply buried, the shales become more compacted, and consequently the maximum available pressure in a given reservoir would be increased with depth. In this way there is a relation of maximum pressure to depth in the upper 10,000 feet of sediment. However, pressures do not necessarily increase with depth as would be indicated by the term "rock pressure." The amount of water originally in the reservoir and the tightness of the surrounding shales are other factors which may greatly change any relation of accumulated pressures to depths. A buried sand deposit may be completely filled with water and surrounded by a very fine shale, so that a small amount of settling[1] would increase

[1] In this paper it is assumed that settling of the strata has caused the fluid pressure in water sands of most of the mid-continent oil pools. With various degrees of saturation in sands of irregular sedimentation, the resulting fluid pressures after settling would be quite variable and irrespective of depth. Such is the case through-

the pressure on the water over that of a deeper sand, which might not have been so nearly saturated nor surrounded by so fine a shale.

The following estimate is made to show that the amount of oil in any producing field could have been derived entirely from shales immediately surrounding the oil sand. A series of shales aggregating 10 feet of bituminous sediment, yielding 25 gallons to the ton would furnish 17,000 barrels of oil per acre. Assuming a 25 per cent extraction, the acre yield would be over 4,000 barrels. The average acre yield in Oklahoma and Kansas ranges from 2,500 to 3,000 barrels. In case of 30,000-barrel-acre yield, which is a rare exception, the total amount of oil, considering a 25 per cent extraction, could be had from an acre bed of shale aggregating 50 feet of bituminous material yielding 40 gallons to the ton. Large acre yields are probably due to concentration in the sand along zones of exceptional openings, and the oil might have been drained from an area of several acres.

CONCLUSION

The foregoing evidence leads to the following conclusions:

1. Bituminous shales are in close relationship with the producing sand of an oil field.

2. This bituminous material is in solid form and is only changed to petroleum in local areas of differential movement.

3. After such a change is made, the accumulation of oil into commercial pools is accomplished by capillary water; and this interchange only takes place in local areas where the oil-soaked shale is in direct contact with the water of the reservoir rock. Such conditions are explainable either by joints or faults.

4. After the oil once reaches the sand, some adjustment takes place until the oil has found the larger openings and then it remains there indefinitely.

---

out the Pennsylvanian rocks of Oklahoma, Kansas, and Texas. Moreover, in a number of cases the water may be reduced or exhausted by pumping the same as the oil, and the decline in production is according to the regular PV curve, showing that the pool is not connected with a source of supply, but has a definite volume in a definite space.

5. The amount of oil in any field could have been derived from normal bituminous shales in close proximity to the pay horizon.

6. These five statements also lead to another general conclusion, that areas of maximum differential movement are in accord with anticlinal structures. It has been noted from a study of the majority of pools in the mid-continent field that the maximum sub-surface faulting is found on the flanks and sides of the anticlines, and that the best production runs in trends parallel to the faulted zones. It has also been noted in a number of cases that production which is not related to marked anticlinal or dome structure bears the same close relation to sub-surface faults.[1]

The author is indebted to many co-workers in the sub-surface branch of the geology department of the Empire Gas and Fuel Company, who have diligently collected and compiled information. Especially is acknowledgment made to Mr. Gerald E. Moser for the diagrams in this paper; to Mr. E. A. Trager for aid in the experiments; to Dr. L. C. Snider for suggestions and criticisms in the work; and to Mr. Everett Carpenter, whose advice and counsel have made the investigation possible.

[1] Detailed data for the basis of these statements are necessarily considered confidential and cannot be published at this time. It is hoped that this material may sometime be available so that a paper discussing the details of various producing structures can be published.

SOME STRATIGRAPHIC AND STRUCTURAL FEATURES OF THE PRE-CAMBRIAN OF NORTHERN QUEBEC

H. C. COOKE

PART III

CORRELATION

In this region, where the sedimentary series do not form any large or continuous sheet, but are found merely as comparatively small remnants separated by wide areas of intrusive granite, it is obviously impossible to make an unquestionable correlation. If in some yet unexplored district there should be found large continuous sheets of sediments which might serve as definite horizon markers over a large area, as the Cobalt series does in the Cobalt-Sudbury-Lake Huron district, a good correlation may eventually be obtained. But under present conditions the criteria on which we must rely for correlation purposes are (1) petrographic similarities; (2) similar geological successions; (3) similar deformations; (4) similar relations to older and younger formations.

PONTIAC-MATTAGAMI-BROADBACK-BROCK SERIES

The patches of sediments known at present under the local names Pontiac, Mattagami, Broadback, and Brock series have strong petrographical similarities. In each the principal rock is a schist which is probably the metamorphosed equivalent of a more or less impure sandstone or sandy shale. It is now composed of quartz and ferromagnesian mineral, with a little feldspar; the ferromagnesian mineral is usually biotite, which locally is replaced by muscovite or hornblende. The muscovite schist probably represents an originally fairly pure sandstone, and the hornblende schist a ferromagnesian sand. The more acid types may have derived their material largely from granitic sources, the more basic types from the basic lavas. The mica schists

grade toward the base of the series into arkoses, greywackes, and conglomerates, which are of essentially the same composition as the schists above them, and differ only in their coarser grain.

This greywacke-like composition indicates that in each of the widely separated areas the sediments were derived by fairly rapid disintegration and erosion of older rocks, without extended decomposition of their constituents by atmospheric weathering. Had decomposition been complete and erosion slow, a better separation of the products of disintegration would have taken place, with resultant deposition of a normal sandstone-shale series. The band of quartzite found in the Kenoniska area is the only one observed in which fairly good segregation of the sedimentary material has taken place; yet its significance is not great, as the bed is thin and the quartzite very impure.

The petrographic similarities indicate that the sediments of the different areas were derived from similar sources, and that similar conditions of weathering and erosion were operative at the time each was laid down.

The succession of the different rock types also affords some evidence for correlation. At the base of each series is a conglomerate bed several hundred feet thick. The composition of this conglomerate is in every case similar—pebbles of granite and the underlying series of basic lavas, with their associated tuffs, cherts, and intrusives, imbedded in an impure sandy matrix. Above this, except in the Mattagami area, lies a coarse-grained arkose, greywacke, or grit, which passes upward into finer-grained material of much the same composition, now metamorphosed to mica schist. In the Mattagami area the conglomerate passes into the upper schist by a decrease in the size and number of the pebbles, without the intervening band of arkose; in the Kenoniska area a narrow band of impure quartzite lies between the arkose and the mica schist.

The succession is one which indicates an almost identical history of deposition in each of the areas under consideration. If the series is of marine origin, the history is one of deposition in a gradually deepening sea or of a subsidence of the land from which the sediments were derived. The absence of shale and

limestone members in every case is also significant of the prevalence of similar conditions of deposition over the whole region.

Structural similarities form perhaps the best evidence for the correlation of these patches of sediment. Each area is a remnant of a close fold, and the amount of deformation during folding was approximately the same in all. On the flanks of the folds the whole body of rock has been converted into schist, even the competent basal conglomerate. The pebbles of the conglomerate in each case have been flattened and sheared, the softer stretched to mere strings, while the hard granites have suffered very little. The axes of the folds show remarkable similarity in strike. The general strike of the Pontiac area is east-west; of the Mattagami area, N. 80° E.; the axis of the Kenoniska and Lucky Strike folds strike S. 75° E.; of the Brock fold, N. 85° E. These variations in strike are very small, considering how widely the districts are separated from one another, and the conclusion therefore seems justifiable that all of these sediments preceded, and were deformed by, one period of regional stress. As the region has been gently cross-folded, the variations in strike most probably are due to this, though perhaps also in part to disturbance by the later intrusion of the granite batholiths.

The different patches of sediments are similar in their relations to the older lava series. In almost every case it has been shown that the sediments rest unconformably on the lava series, since the basal conglomerate contains rounded pebbles of all the underlying rocks. As to the nature of the unconformity, a close parallelism of strike and dip obtains between the two series, indicating either that they were folded at one time or that a possible earlier gentle folding of the lavas was obscured by more intense shear after the sediments were laid down. In the case of the Kenoniska and Lucky Strike areas, the basal conglomerate was observed to rest on different types of rock from point to point, but whether this was due to differential erosion of the underlying rocks previous to the deposition of the conglomerate or to original irregularities of deposition in the underlying series was not determined with certainty. It is believed, however, to have been due to erosion, since in the case of the Lucky Strike area

the conglomerate at its most easterly observed contact rests upon garnetiferous mica schists, which are believed to be the metamorphosed equivalent of a once widely distributed sediment, the Nemenjish series, while farther to the west it rests directly upon basic lavas. In addition, the presence of the thick basal conglomerate indicates that the erosion of the underlying series was great before the deposition of the upper. In the undeformed conglomerate of the Kenoniska area, none of the basic pebbles possess schistosity; so that the lava series could not have undergone serious deformation before the conglomerate was laid down.

The similarity of the relations which prevail among the different patches of younger sediments toward the older series of lavas and sediments still further strengthens the probability that these patches originally formed part of a single widespread formation. The unconformity appears to be one of erosion mainly, with little or no structural discordance.

As regards the relations of the sediments to younger formations, the only younger rock in contact with all of them is the granite, which in each case intrudes them. As there is no sedimentary rock younger than the granite in the region, by which its age may be checked, the granite does not afford any adequate datum plane for correlation purposes.

Summary.—It has been shown that in the patches of sediments now known under the local names of Pontiac, Mattagami, Broadback, Lucky Strike, and Brock series, there are several striking similarities: (1) The character of the sediments shows that they were in each case derived by the disintegration and erosion of a land area, which went on with such rapidity that the component minerals of the eroded rocks were not highly decomposed; as a result, the sediments are not characterized by a normal sandstone-shale alternation, but are of a greywacke or arkose composition throughout. (2) The absence of the metamorphosed equivalents of limestone or shale, of which latter sediment there must have been some quantity, indicates fairly shoal water or subaërial conditions during the deposition of each series. (3) The succession in each case is similar; a conglomerate lies at the base, overlain by finer-grained material, arkose or greywacke, of essentially the

same composition, which in its turn is overlain by biotite or hornblende schists, representing similar material in a still finer state of subdivision. The succession indicates a similar history in each case. (4) The relations of each body of sediments to the underlying lava series appears to be one of erosional unconformity; if structural unconformity also exists, the discordance is slight. Thus the period elapsing between the outpouring of the lavas and the deposition of the sediments was characterized in each case by gentle epeirogenic movements only, not by intense orogenic movement. (5) The close parallelism of the axes of the major folds of the different areas indicates that all were deformed either by the same force or by successive forces directed along the same lines; while a study of the effects of shear on the different folds shows that each body of sediment was deformed to about the same extent. These two lines of evidence indicate that all the sediments were folded at the same time, and by stresses of much the same strength. (6) All the sediments have been intruded by granites, which, though not proven to be of the same age, have not as yet been shown to be of different ages.

While, as previously stated, an entirely reliable correlation in these pre-Cambrian rocks cannot be made in the absence of a continuous sedimentary datum plane, nevertheless the foregoing evidence indicates such a uniformity in the history of these scattered patches of sediments that it appears highly probable that they are remnants of a single, once widely distributed formation or series. So far as now known, this series may have been deposited under marine conditions and have formed a continuous sheet, or under continental conditions in separate settling basins. As the time has not yet arrived for the correlation of these sediments with other ancient sediments to the south and southwest, such as the Timiskaming, Sudbury, and Hastings series, the writer would apply a single local name to all those under discussion, simplifying the nomenclature by the elision of the various local names already applied. The name Pontiac series, applied by M. E. Wilson in 1909 to the sediments of the first discovered belt to the south, has precedence; but in view of the doubt as to the composition of Wilson's Pontiac series, as outlined on page 200,

the name "Mattagami series" will be used until the doubt is cleared up and the term "Pontiac" re-defined, if necessary. In the remainder of this paper the term "Mattagami series" will therefore be used to include the original Mattagami series, the Broadback, Lucky Strike, and Brock series, and the conglomerate-arkose portion of the Pontiac series to the south.

Age.—The Mattagami series has been shown to consist of scattered patches of sediments, all of which are older than a great orogenic movement and a period of granitic intrusion. In the southwest corner of the region under discussion, the Mattagami series is overlain by the flat-lying Cobalt series, which rests on a peneplain that bevels the Mattagami series, the intrusive batholiths of granite, and the older lavas indiscriminately. A very long period of erosion must have ensued therefore between the end of the deposition of the Mattagami series and the commencement of the deposition of the Cobalt series. The Cobalt series has recently been shown by W. H. Collins[1] to be of the same age as the upper part of the original Huronian series of the north shore of Lake Huron. It is separated there from the lower part of the Huronian, which Collins has termed the Bruce series, by an unconformity, represented by the erosion of some 1,600 feet of sediments and a gentle folding. The Bruce series has been shown by Collins[2] to be very similar in the character and succession of its members to the Lower Huronian of the Marquette region. The erosion plane dividing the Cobalt series and the older rocks in northern Quebec passes southward beneath the Cobalt series in the Cobalt district, and beneath the Bruce series in the Lake Huron district. It may safely be stated, therefore, that the Mattagami series is of pre-Bruce age, and therefore probably pre-Lower Huronian, and that it antedates the Bruce by an interval sufficient for orogenic forces to raise a mountain range of unknown height, and for the forces of erosion to reduce this range toward its southern side at least where the Bruce series was deposited, nearly to base-level.

[1] W. H. Collins, *Geol. Surv. Can., Museum Bulletin No. 8*, 1914.

[2] W. H. Collins, memoir in preparation.

NEMENJISH-GRENVILLE SERIES

A series of rocks which are the metamorphosed equivalents of clastic sediments has been termed the Nemenjish series in the foregoing pages. They attain their largest extension in the contiguous Windy Lake and Nemenjish areas. These rocks are believed to be the northern equivalent of the Grenville series.

The primary basis for this tentative determination is petrographic. It is recognized clearly that petrographic similarities as a rule form a most insecure foundation for correlation; but the petrographic peculiarities of these rocks are so marked and so different from those of any other rocks observed by the writer in the pre-Cambrian of Ontario or Quebec that they afford unusually good evidence for this purpose. The major portion of the rocks, above the basal beds, are highly garnetiferous. They consist of rather fine-grained, light grey mica gneisses or schists, and greenish-black hornblende gneisses, crowded with small, light pink garnets. The garnets in the mica gneiss are usually small, 1–2 mm. in diameter; those in the hornblende gneiss usually somewhat larger, 3–5 mm. in diameter. *Garnetiferous types probably average at least 50 per cent of the total bulk.* No such bulk of garnetiferous rocks is found in any other pre-Cambrian series. Garnetiferous types, usually garnetiferous hornblende schists, occur locally in the altered basic lavas, often termed "Keewatin," and also in the Mattagami series, but invariably in minor amount, less than 1 per cent. The writer therefore considers this criterion as a reliable one for correlation purposes, until it shall have been shown that another formation with similar bulk characteristic exists in the pre-Cambrian shield.

The Grenville series extends north of the Ottawa River at Ottawa for approximately 140 miles, almost to the junction of the east and west branches of the Gatineau River. It is bounded on the north by a great batholith of granite intrusive into it. A section made by the writer in 1916 down the Gatineau River from the National Transcontinental Railway to Ottawa showed that within the boundaries mentioned above the continuity of the series is unbroken, except by relatively small granitic

intrusions. Over a distance of about twenty miles south of its northern boundary the Grenville contains little crystalline limestone but is composed almost entirely of altered clastics, largely garnetiferous, of types identical or almost so with the Nemenjish series. Farther to the south, where crystalline limestone forms a large proportion of the Grenville, much of the remainder is composed of garnetiferous mica gneisses like those of the Nemenjish series.

A gap of about 140 miles exists between the Nemenjish series and the Grenville, occupied by a great batholith or batholithic complex of granite, which has an east-west extension from near the Bell River at least to Lake St. John, about 250 miles. The correlation of the two series across this belt of granite would appear at first sight a hopeless task; but it is rendered possible by the fact that the eastern end of the batholith is not deeply eroded, in fact is apparently barely unroofed. Across its whole width[1] thousands of inclusions of the Nemenjish or Grenville rocks are present, of all sizes and in all stages of digestion. These are so numerous that it is rare to find a single small outcrop of granite without undigested inclusions whose original nature is recognizable. In size the inclusions vary from small lumps a few inches or feet in diameter to large bodies several miles in length, which are probably true roof pendants. In freshness they vary from sharp-angled bodies with little or no trace of the solvent action of the granite to completely dissolved forms now represented by garnetiferous micaceous bands in the gneiss. A very characteristic trade-mark of the interaction of granite and sediment is the presence of garnet, which seems to have dissolved during the digestion of the sediment and subsequently to have recrystallized with little or no change. The formation of such digested products is so well shown in all its stages that even the end products of the reaction might safely be taken as evidence

[1] The sections studied by the writer, where such large numbers of garnetiferous inclusions were observed, were those of the St. Maurice River, from the Transcontinental Railway to Sandy Beach Lake, and thence northward across the Height of Land to Askitichi Lake; and from the Hudson Bay post at Kikendatch across to the headwaters of the Gatineau, and down the Gatineau. Farther to the west erosion appears to have removed greater thicknesses of granite; correspondingly the number of inclusions become smaller toward the west, and the proportion of those which have undergone complete or fairly complete digestion increases.

of the former presence of the sediments; but it is not necessary to rely on these as there is a sufficiency of the comparatively unaltered fragments for purposes of recognition. The highly garnetiferous character of the greater number of them renders their derivation from the Nemenjish or the Grenville series almost indubitable.

Summary.—The writer bases the correlation of the Nemenjish series with the Grenville series on the following facts: (1) The Nemenjish series possesses unusual petrographic characteristics, in that approximately 50 per cent of the rocks of the series are garnetiferous. (2) The granite batholith separating the Nemenjish and the Grenville series is loaded with recognizable inclusions of these peculiar garnetiferous schists. (3) The composition of the Grenville on the southern border of the granite batholith is identical with that of the Nemenjish series, i.e., garnetiferous mica and hornblende gneisses, with a little crystalline limestone. This passes to the south into Grenville of normal composition by increase in the amount of limestone, without much change in the character of the altered clastic members.

Relations to older formations.—The relation of the Nemenjish series to the lava series appears to be one of perfect structural conformity, although this determination is weakened by the fact that the contact was observed at one place only. As described, the sediments were found resting on the old surface of a basaltic lava flow, and with the same dip and strike as the lava. At the contact the sediments were thin beds similar to the tuffs elsewhere observed interbedded with the lavas; but these became mingled with beds of sediments similar to the overlying material a short distance above the base, and within a few hundred feet were entirely replaced by them. When these sediments were first seen, it was supposed that they probably belonged to the Mattagami series, and a very careful search was made along the contact with the lavas for evidences of unconformity, but none were found. There is not a trace here of the conglomerate which uniformly lies at the base of the Mattagami series, and appears to be at least 300 feet thick wherever it has been possible to measure it. There is no evidence of the presence here of any large

Department

fault, which might have brought the two series into intimate contact. It would appear therefore as if there was no discordance, structural or erosional, between the sedimentary series and the underlying extrusive rocks.

The problem presents itself, however, of explaining why the Nemenjish sediments here rest upon basalts, which have been shown to form elsewhere the basal rocks of the lava series, rather than upon its higher members. On the creek flowing from Little Nemenjish Lake to Obatogamau Lake, five miles to the east, the sediments overlie andesites, although the contact is not exposed.

Two hypotheses present themselves. There may have been a period of erosion intervening between the extrusion of the lavas and the deposition of the sediments, so that where the sediments rest on the lower members the younger lavas may have been removed by erosion; or the younger lavas may never have been extruded in these localities. The first hypothesis appears inadmissible, on account of the perfect conformity and lack of any trace of basal conglomerate or coarse basal sediments. If the second hypothesis be true, then some of the lower beds of the Nemenjish series must be equivalent in age to the upper lava flows, unless conditions were such that no sediment was deposited during the period intervening between the extrusion of the earliest and latest lavas. We might therefore expect to find at some point an interbedding of the sediments with the higher lava flows. This is actually the case on Kaopatina Lake, where a thin flow of rhyolite porphyry in interbanded with the sediments. In this case, the beds with which the flows are interbanded are not of true clastic material, but appear to be made up in part of cherty material, perhaps a chemical sediment, and in part of fine-grained, rather basic material, perhaps volcanic dust or the first products of erosion of the lava fields. In the critical section of the Opawika River above Kaopatina Lake, beds of similar composition were observed to lie at the base of the Nemenjish series, and to grade up into it by a gradual increase in the proportion of normal clastic material.

It seems probable therefore that the whole region was not covered by uniform sheets of lava of the same composition, but

that as might be expected, the extrusions were more or less localized, so that the Nemenjish series may lie from place to place on different types, but still maintain conformable relations. Further, it appears that the sedimentation was slight during the whole extrusive period, and largely confined to deposits directly or indirectly from volcanic sources. Lava flows may be interbanded with these sediments, but the extrusion of these was complete before the true clastics became large in amount, as the two have never been found interbanded.

Relations to younger formations.—Since the Nemenjish series rests conformably on the lavas in the Windy Lake area, and the Mattagami series rests unconformably on the lavas in the Brock and other areas, it might be supposed that the Mattagami series is younger than and unconformable on the Nemenjish series. This conclusion assumes that the lavas in the different areas are of the same age. Direct field evidence bearing upon the relation of the two sedimentary series is very scanty. The only areas furnishing such evidence are the Kenoniska and Lucky Strike areas, where garnetiferous mica schists are found lying between the Mattagami basal conglomerate and the underlying lavas. The petrography of these rocks makes their correlation with the Nemenjish seem probable, and they lie unconformably beneath the Mattagami series.

The Nemenjish-Grenville series is intruded by all the plutonic rocks of the region, and is therefore older than all. An older granite intrudes it in the vicinity of Lake St. John. Later, it was cut by great masses of anorthosite. Finally, it was cut and, in this region, almost entirely stopped away and digested by the great batholithic intrusions of granite which followed the deposition of the Mattagami series.

LAVAS

The lavas of the region under discussion appear to be of a single age, so far as the evidence at hand indicates. They are very similar in their petrographic character and in the extent of their metamorphism. Wherever their succession has been worked out, it is the same; basaltic lavas form the lowest exposed beds, overlain successively by andesitic lavas, andesitic tuffs, and

rhyolitic lava or tuff.[1] Wherever sediments of Nemenjish age have been found the lavas underlie them conformably. Wherever patches of the Mattagami series occur, they overlie the lavas with unconformity. Wherever anorthosite masses outcrop, they intrude the lavas.

As these lavas, like the Mattagami series, underlie the great erosional peneplain that underlies the Cobalt series, it is possible that they are to be correlated with the lavas in the Cobalt district, which are there known as "Keewatin" and which occupy a similar stratigraphic position. There is as yet, however, little or no evidence for correlating these lavas with the Keewatin of the north and south shores of Lake Superior. The local name of Abitibi volcanics will therefore be extended to apply to the lavas in this whole region. This name was first applied by M. E. Wilson in 1909 to the lavas in the Kewagama map-area, in the southwestern part of this region.

ANORTHOSITES

Anorthosite and anorthositic gabbro do not appear to any large extent within the region under discussion. A mass of considerable size is found on the Bell River, near Mattagami Lake, another on Chibougamau Lake. Smaller masses are found on the Opawika and Chibougamau rivers; there is an immense mass in the vicinity of Lake St. John. To the east and south of Lake St. John, the amount of anorthosite is much larger; it is also present in large amount in the Adirondacks.

Since anorthosite may be formed as a differentiate of any gabbroid magma under suitable conditions, and since it so happens that the anorthosite masses are not as a rule in contact with a sufficient number of sedimentary formations for their age to be closely determined there is little or no evidence that they may not be of more than one age. However, the occurrence of such great masses of anorthosite has been rare throughout geologic history. Hence it is considered highly probable that all of the anorthosite belongs to a single period of igneous activity and owes its origin to some common cause.

[1] It may be here mentioned that the writer's work of 1917–18 has shown that the simple succession described for the lavas of northern Quebec does not prevail in the Montreal River district of northern Ontario.

The age of the anorthosite, while not definitely fixed, may tentatively be placed as post-Grenville and pre-Mattagami. In the Lake St. John district it has been found to intrude the Grenville, and also to intrude an earlier granite which also intrudes the Grenville. It is itself intruded by the later granite that cuts the Mattagami series. It has never been found in direct contact with the Mattagami series. A mass of anorthositic gabbro on the Bell River intrudes the Abitibi volcanics but does not rise as high as their contact with the Mattagami series. In the Lucky Strike area a single pebble of what was supposed to be anorthosite was observed in the basal conglomerate of the Mattagami series. This pebble could not be got out of the matrix for microscopic study, however, so that its exact determination is uncertain. The age of the anorthosite can, therefore, only be placed tentatively as pre-Mattagami.

GRANITES

In the vicinity of Lake St. John, J. A. Dresser[1] has reported the presence of granites both earlier and later than the anorthosite there. To the northwest of the lake all the granite observed is later than the anorthosite. To the south and east of the lake, Adams[2] has reported that the granite is earlier than the anorthosite. In New York state, Cushing, Kemp, and Smyth state that the anorthosite is later than the gneisses which intrude the Grenville series. The existence of granites of two ages therefore seems to be fairly definitely established. The earlier of these seems to have been confined in its distribution to the south and east of Lake St. John; in age it postdates the deposition of the Grenville series and antedates the intrusion of the anorthosite masses. The later granite was intruded mainly throughout the region to the north and west of Lake St. John, though it is also found in small amount to the south and east. In age it is pre-Cobalt, but is later than the anorthosite intrusions and the deposition of the Mattagami series.

[1] *Geol. Surv. Can., Mem. No. 92*, 1916.

[2] *Geol. Surv. Can., Ann. Rept., New Ser.*, VIII (1897), Part J.

[*To be continued*]

A PLANIMETER METHOD FOR THE DETERMINATION OF THE PERCENTAGE COMPOSITIONS OF ROCKS

ALBERT JOHANNSEN
University of Chicago

The great objection to the Rosiwal method for determining the composition of rocks lies in the nerve-racking necessity of continually reading the stage-micrometer, and the length of time required for the process. In a recent paper in the *Journal of Geology*, Shand[1] described a mechanical stage by the use of which very few readings are necessary. An instrument of this kind undoubtedly would greatly reduce the labor of computing the composition of a rock and tend to make the method more popular. Unfortunately few laboratories are likely to have such a stage; but with the equipment on hand in most institutions, measurements more rapid and possibly more accurate may be made.

Many years ago Delesse[2] determined the compositions of rocks by tracing, on oiled paper, the outline of each component as shown in polished slabs. After coloring his drawing he pasted it on tin foil, cut apart and sorted the different components, soaked off the paper, and weighed the tin foil. Later, Sollas[3] applied the method to thin sections by using a camera lucida, and Joly[4] used photomicrographs. Since Rosiwal[5] introduced his method of linear measurements in 1898, it has been the system commonly used.

[1] S. J. Shand, "A Recording Micrometer for Geometrical Rock Analysis," *Jour. Geol.*, XXIV (1916), 394–401.

[2] A. Delesse, "Procédé méchanique pour déterminer la composition des roches," *Comptes Rendus*, XXV (1847), 544–45; see also article, "Procédé méchanique pour déterminer la composition des roches," *Ann. d. Mines*, XIII (1848), 379–88.

[3] W. J. Sollas, "Contributions to a Knowledge of the Granites of Leinster," *Trans. Roy. Irish Acad., Dublin*, XXIX (1887–92), 471–73.

[4] J. Joly, "The Petrological Examination of Paving-Sets," *Proc. Roy. Dublin Soc.*, X (1903–5), 62–92.

[5] August Rosiwal, "Über geometrische Gesteinsanalysen," *Verh. d. k. k. geol. Reichsanst.*, Wein, 1898, p. 143.

The method described below is based on surface measurements. As will be shown, these are proportional to volumes in any uniform, non-banded rock, irrespective of the shape of the individual components.

Place a camera lucida over the eyepiece of the microscope and block up a drawing-board at the side so that the field of view is not too large, say four or five inches in diameter. Tilt the microscope or incline the plane of the paper until the drawing is not distorted. This may be determined by tracing the projection of a circle or square upon the paper and measuring it in several directions. If no object-glass with circle or square is at hand, place an ordinary object-scale successively vertically at the right and left of the field of view, and horizontally at the top and bottom, and lay off equal distances in the projection. If equal divisions on the scale are equal everywhere in the drawing, the plane of projection is at the proper angle or the microscope is properly tilted.

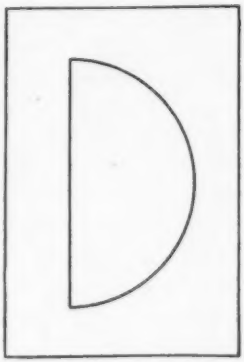


FIG. 1

Place one edge of a thin straight-edge of wood, celluloid, or cardboard on the drawing-board along the projection of the vertical cross-hair as seen through the camera lucida, and fasten it with thumb tacks. This is to serve as a guide for the stylus of a planimeter, as described below. Instead of a straight-edge, the writer uses a piece of celluloid about 1 mm. thick, in which is cut a semicircle (Fig. 1) exactly the size of the field of view ($4\frac{1}{2}$ inches in his microscope with a 31-mm. objective).

Select the objective most suitable for the particular rock section in hand; the lower the power, the better. Place a typical area in the field of view, and make on the cover-glass, on the line of the vertical cross-hair, a mark in red ink to indicate the starting-point. Place a planimeter on the drawing-board in such a position that the base will not interfere with the projection of the section as seen through the camera lucida.

Place the stylus of the planimeter at the top of the field of view and on the vertical cross-hair (Fig. 3, *A*). The writer replaces the ordinary stylus by a heavy wire bent as shown in Fig. 2, so that the end of the planimeter bar will not interfere with a view of the end of the needle point. Adjust the length of the planimeter bar so that when the stylus is moved around the semicircle (Fig. 1), that is, half the field of view, it will register exactly unity (10 or 100). This adjustment, of course, is not necessary, but by making it all readings are in percentage values without conversion; otherwise it is necessary to reduce the sum of the readings to 100.

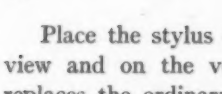


FIG. 2

Record the reading of the planimeter or set it to zero by rotating the wheel. If the bar has not been set to read 100 for the field of view, move the stylus around the periphery of the field in the proper direction, right or left, to record additions, and read again. The difference will give the area of a single field. Again set the planimeter at zero, and, beginning at *A*, move the stylus along the straight-edge to the periphery (Fig. 3, *B*) of the first grain of the particular mineral chosen for the first determination, say biotite in granite. Trace the outline of this grain and *remember always to move the stylus in the same direction of rotation*. It will be necessary in the first readings to lift the stylus point on top of the straight-edge to record the left-hand portion of the mineral. Having returned to the point *B*, without reading the planimeter move along the straight-edge to *C* on the periphery of the next grain of biotite *lying on the line of the vertical cross-hair*, and move around it in the same way and in the same direction back to the point *C*. If the mineral of the kind being measured lies in the center of the circle (Fig. 3, *D*), it is always to be measured in

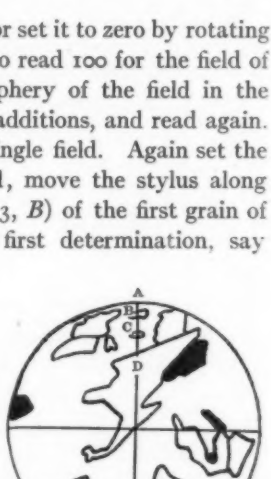


FIG. 3

the first series of readings for that kind of mineral so that it may not be forgotten.

Rotate the stage of the microscope to the left until the left margin of another grain of biotite is *just tangent* to the cross-hair. Though the point D at which the stylus rested on the outline of the last mineral measured is moved to D' (Fig. 4) the stylus in the projection, of course, still rests at D. From this position move upward or downward to the periphery E of the new biotite grain tangent to the cross-hair and trace its outline in the same direction as before. Rotate the stage until another grain is tangent to the cross-hair, trace its outline, and so continue until all of the grains of biotite in the section have been measured, and the red spot again lies on the vertical cross-hair. The object of rotating the stage of the microscope only so far as the point of tangency of each new grain is to avoid confusion and the repetition or omission of some fragment. Movements up and down along the straight-edge, being plus and minus, are not recorded when the stylus again rests at A. When all the grains of this species of mineral have been measured and the *stylus has been returned to the point* "A," record the planimeter reading and subtract the preceding reading from it. This gives the total area of the first mineral measured. If there are any inclusions in a mineral they may be deducted by moving them to the point of tangency and rotating the stylus around them in reverse direction.

FIG. 4

Begin with the red mark on the slide again at the top of the vertical cross-hair and measure a second variety of mineral in the same manner as before, and so on until all the minerals are determined. It is usually well to measure the more pronounced or least abundant minerals first, leaving for the last the most abundant, least pronounced, or groundmass mineral. A slight error in the other readings will change the true percentage less

by leaving the most abundant mineral to the last and recording it as the difference. As a check, the last mineral should be measured and the sum of all the readings should be the same as that of the field of view.

In tracing the peripheries of the mineral grains, when they are very irregular, it is not necessary to follow their outlines absolutely; the little variations from one side to the other compensate. Furthermore, hackly ends may be averaged, long needles traced to half their length but twice their width, and so on, the results being usually more accurate than if the actual outlines are followed. Where there are a number of very small grains, as of magnetite, they may be estimated and a circle described by the stylus approximately equal to their sum. A little experience will show what may be done in the way of short cuts.

The number of fields of view to be measured in a rock slide depends upon its uniformity of texture, the mineral distribution, and the size of grain. With small grains and uniform distribution of minerals, a single field may suffice. With coarser grain or unequal distribution, it may be necessary to take as many fields as will cover the entire thin section, or it may be advisable to use several sections. If the mineral grains do not fill the field of view, or if there are pore spaces, it is only necessary to deduct the readings of these from the reading of the circle of the entire field of view and reduce the sum to 100.

The measurement of the dark minerals is easy, but the separation of the colorless minerals may give trouble. Before running the outline of one of these, it is usually well to swing off the camera lucida, insert the analyzer, and rotate the stage to various positions until the boundaries are clearly in mind; then, after replacing the camera lucida, place the edge of the mineral tangent to the vertical cross-hair as before and, with the nicols still crossed, trace the outline. The writer uses a Leitz microscope with simultaneously rotating nicols which makes it unnecessary to disturb the position of the stage; the nicols only are rotated until the mineral appears in its most pronounced color.

With crossed nicols, or when separating minerals of different refractive indices by partially closing the lower diaphragm, it

may become necessary to cut off some of the illumination from the paper. This, of course, is done by inserting the blue glass screens provided with the camera lucida. In other cases, when the light from the stage is too bright, the blue glass may be swung to that side, or, more simply, a blue glass may be placed over and parallel to the thin section and below the objective, or some of the light may be cut off by holding a finger before the mirror, by tilting it, or by partially closing the lower diaphragm. In some cases one method is best; in others, another. Sometimes the drawing or the mineral is made more distinct by simply holding the eye at a greater distance from the camera lucida.

THE BUTTE QUARTZ MONZONITE MEASURED BY PLANIMETER

The writer uses volume percentages for his determinations instead of weight percentages. For example, a rock is half-light and half-dark to the eye when the volumes are 50–50 and not when their weight percentages are 50–50. Thus a rock half plagioclase and half magnetite by volume would have the proportions 34.4 to 65.6 by weight. In the following table, therefore,

	Rosiwal Determinations by Four Different Students on the Same Slide Volume Percentages				Average of Preceding	Average of Following	Planimeter Determinations on Four Different Areas of Same Slide as First*							
							First Area		Second Area		Third Area		Fourth Area	
Quartz.....	14.80	17.24	18.07	17.24	16.84	18.4	22.9	22.0	17.5	18.0	18.1	17.9	15.1	14.8
Orthoclase....	34.52	26.01	27.80	22.54	27.72	28.5	20.3	19.8	30.2	31.0	31.5	31.8	31.6	32.1
Plagioclase...	34.52	45.50	38.67	42.46	40.29	39.9	46.8	47.2	36.6	36.0	34.1	33.9	42.7	41.8
Biotite.....	7.07	5.30	9.67	9.84	8.19	7.4	4.5	5.4	8.3	7.8	9.2	8.9	7.7	7.9
Pyribole.....	7.07	4.48	4.61	7.76	6.13	5.2	5.0	5.2	5.9	6.0	6.9	7.0	2.6	3.0
Magnetite....	.44	.48	.55	.16	.41	.4	.1	.1	1.2	1.0	.....	.....	.3	.4
Pyrite, etc....	.07	.95	.58	.....	.40	.2	.4	.3	.3	.2	.2	.5	.....	.....
	99.99	99.96	99.95	100.00	99.98	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

*The volume percentages by the planimeter method here given are not to be compared with the weight percentages in the paper by Johannsen and Stephenson in the preceding number of this *Journal*, since they represent a single and not typical slide; namely, the one shown in the first column of Table III in that article.

volume percentages are used. The first four columns give the Rosiwal readings made by four different students on the same slide of Butte quartz monzonite; the fifth column is their average. The sixth column is the average of eight planimeter readings on four fields of the same slide. The similarity of each pair of readings is to be noted. The differences shown by the four fields are

not due to errors of reading but to actual differences in different portions of the slide, the rock being coarse enough to show such variations. It is true that the planimeter readings were all made by one person and not by different individuals, which may account somewhat for their similarity, though clearly showing that the error cannot be great. The averages obtained by the two methods are very similar in spite of the fact that some of the students' readings are clearly in error.[1]

The length of time required for a planimeter reading of a single field of a rock of the character of the one here used is about ten minutes or less. Using four fields, a complete determination can be made with ease in three-quarters of an hour, and without any great mental strain during the process.

RELATIONSHIP BETWEEN AREAS AND VOLUMES

In the discussion of the relationship between surface and volume measurements, the mistake has commonly been made of considering this as a comparison between d^2 and d^3 to D^2 and D^3, where d is the length of a side of a square representing the sum of all grains of the same mineral appearing in a section, and D the side of a square representing the entire surface. As a matter of fact, in a rock with uniformly distributed particles, this is not the relationship at all, for if the mineral grains under consideration were floated to one side of the cube they would make a thin tablet, one dimension (d_1) depending upon the abundance of the mineral, each of the other two equal to the side of the large cube (Fig. 5, D). In the Rosiwal method this is the way in which the minerals are to be considered as placed, and each Rosiwal reading from west to east includes the proper proportion of the mineral. The surface value is d_1D, not d_1^2, and the volume d_1D^2, not d_1^3. If one measures areas, the mineral may be considered floated to

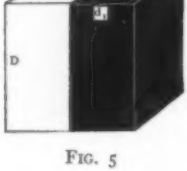


FIG. 5

[1] In explanation it must be said that the determinations here given were the students' first efforts with the Rosiwal method. The planimeter determinations are by the writer.

a vertical edge (Fig. 6) forming a vertical prism whose dimensions are d, d, and D; the value of d, of course, differing from the d_1 value but such that $Dd_1 = d^2$. The surface and volume values in each case, naturally, are the same. This may easily be seen by considering a solid built up of black and white cubes.

I. CASE OF CUBICAL GRAINS, UNIFORMLY DISTRIBUTED

a) Assume a cube, 10 inches to a side, built up of small black and white inch cubes, uniformly distributed. If the black–white ratio is 50–50, every other block must be black. Moved to one side so that all the black cubes are together (Fig. 5), the number at the surface will be 50, distributed in a rectangle whose sides are d_1 and D (5×10). Moved to one edge the 50 square inches of surface would appear as a square, seven cubes on a side and one left over; in other words, $d = 7.07+$. The total number of black cubes is 500; therefore the volume is not represented by d^3 ($=353.5+$) but by $d^2D = 50 \times 10 = 500$. The relationship, therefore, between the black minerals appearing at the surface to the entire surface is as $\frac{d^2}{D^2}$, while the volume relation of black to white is $\frac{Dd^2}{D^3}$ and not $\frac{d^3}{D^3}$. But $\frac{d^2}{D^2}$ and $\frac{Dd^2}{D^3}$ are equal; therefore the ratios of surface and volume measurements are equal.

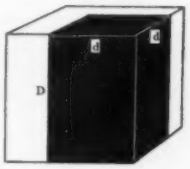


FIG. 6

b) If the ratio of black to white is very small, such as 1 to 10,000, it will not do to assume that the black mineral occurs as a single cube, whose volume is $\frac{1}{10}$-cubic inch, in a 10-inch cube of white, for that would vitiate the original assumption of uniform distribution of constituents. If we say that the ratio of surface to solid is as d^2 to d^3 it means that our mineral all lies in the top layer and is not uniformly distributed. It is comparable to saying that a topaz granite in which an accidental crystal of topaz occupies half the slide is half-topaz, while as a matter of fact there might be but a single crystal to a cubic foot. Consider, therefore, that the small amount of black mineral is uniformly distributed in

cubes measuring $\frac{1}{10}$ inch on a side ($d = \frac{1}{10}$ inch). If now all these small cubes be gathered along one of the vertical edges of the large cube, the portion of the black mineral of the entire block which will appear at the surface (Fig. 6) will be $d^2 = (\frac{1}{10})^2$, and the black–white surface ratio will be $\frac{d^2}{D^2} = \frac{(\frac{1}{10})^2}{10^2} = \frac{1}{10000}$. That is, the black mineral forms .01 per cent of the surface. The volume ratio of black to white is $\frac{Dd^2}{D^3} = 10\frac{(\frac{1}{10})^2}{10^2} = \frac{1}{10000}$. The volume ratio, therefore, is the same as the surface ratio.

II. CASE OF TABULAR PLATES, UNIFORMLY DISTRIBUTED

Let a, b, and c represent the ratios of length, breadth, and thickness of tabular dark constituents. If they are uniformly distributed the same number of flakes will be contained in each layer below the upper surface; consequently no matter what the thickness, Dab represents the volume of the black blocks, while D^3 represents the large block. The ratio of surface measurements to the whole is $\frac{ab}{D^2}$, and of volumes $\frac{Dab}{D^3} = \frac{ab}{D^2}$; consequently the two are equal.

With thinner flakes there would be more layers in the large cube, and with thicker, less. But no matter what the ratio of a to b to c, the surface percentage is the same as the volume percentage, *provided the grains are equally distributed*. Of course a laminated rock, with layer of different minerals, might be so cut that one slide would contain no dark minerals and one no light. A cross-section of such a slide, however, would give correct results, for the distribution at right angles to the slide is uniform.

III. CASE OF CLOSELY PACKED CYLINDRICAL RODS

This case is approximately the same as the preceding, for in one direction in the slide the mineral is continuous while in the other there is interstitial material. Sections should, therefore, be taken at right angles to the elongation. The surface ratio is $\frac{\pi r^2}{D^2}$, and the volume $\frac{D\pi r^2}{D^3}$. As before, the two are the same.

IV. CASE OF SPHERES CLOSELY PACKED AND SQUEEZED TOGETHER

When spheres are closely packed and are then squeezed together they tend to assume the form of dodecahedrons. A cross-section through such a mass will give a series of triangles. If b is the base of such a triangle and h its height, its area is $\frac{bh}{2}$. Nbh will be the area of the sum of such triangles and the ratio to the whole, $\frac{Nbh}{D^2}$. Since every parallel section will give an equal distribution of light and dark, the volume of dark mineral will be $DNbh$ and its ratio to the whole $\frac{DNbh}{D^3}$, which is the same percentage ratio as in the case of the surface measurement.

Thus, no matter what the shape of the individual mineral grains, if they are uniformly distributed the surface ratios are exactly the same as are the volume ratios; consequently surface measurements may be used to represent volume measurements in the determination of the composition of a rock.

GEOLOGY OF FLORIDA

E. H. SELLARDS
University of Texas, Austin

To those who have seen Florida but casually it may seem that the geology of the state is entirely obscured beneath the sand, soil, and vegetation of the prevailingly level surface. But to those who have looked more closely it is apparent that such is not the case. It is true that the problems of geology are made more difficult by the lack of frequent and continuous exposures, but they are not necessarily made impossible of solution. The numerous stream channels, railway and public-road cuts, drainage canals, and drilled wells afford records from which the stratigraphic succession and structure of formations may, with patience and persistence, be worked out. Fortunately many of the formations of the state are richly fossiliferous. Nowhere in the United States do the Tertiary and Quarternary formations contain a more abundant, more varied, or better preserved marine invertebrate fauna than in Florida. In this respect there is an embarrassment of riches. Dr. Dall in his study of the fossils of the Caloosahatchee marl, recognized in that formation alone the presence of more than 600 species of mollusks. Vertebrates, although as a rule not so well preserved as the invertebrates, are relatively numerous. No state east of the Mississippi, perhaps, contains so many Tertiary and Quarternary vertebrates as does Florida. Fossil plants, although less abundant than either invertebrates or vertebrates, are not wanting. It is seldom the case that a single formation holds both land and marine fossils, yet something of an insight into the interrelation of the marine invertebrates, land animals, and land plants is secured in the Florida Miocene and again in the Florida Pleistocene. In the study of the fossils, Florida is in many respects a state of exceptional opportunities.

TOPOGRAPHY AND ELEVATION

In topographic detail and surface configuration Florida is by no means lacking in variety. In this respect the state presents much greater diversity than would have been anticipated in view of the fact that the maximum elevation within the state scarcely exceeds 300 feet above sea-level. In the upland section of the state the intimate relation between topography and geology becomes apparent. The limestones under the influence of a heavy rainfall and an excess of humic acids in the ground water have dissolved rapidly, and when lying near the surface have produced a characteristic topography. The lowlands bordering the coast, on the other hand, have been but little affected by erosion, and in these areas the surface is perhaps but slightly modified from its original condition. Of the land area of the state, approximately one-half lies below the 50-foot contour line. This belt of land below the 50-foot contour includes all of the peninsula south of the northern end of Lake Okeechobee, and in addition a strip of varying width bordering the Atlantic and Gulf coasts. Aside from beach deposits and sand dunes, this belt of country is prevailingly level. The surface deposits are usually sandy, although, as will be subsequently indicated, limestones underlie considerable areas.

The higher lands of the interior of the state present for the most part topographic features that are difficult of description, owing to the apparent irregularity and lack of system of the hills and valleys. Over much of this area the topographic features are the result of the solution of the underlying calcareous deposits, and the prevailing surface configuration includes depressions or solution basins of varying size and depth, and hills of varying size and height. Within the area, the topography of which is controlled by underlying calcareous deposits, are two subdivisions which are worthy of special mention. These are the "sink-hole region," which lies chiefly along the west slope of the peninsula, and the "lake region," which lies for the most part near to or somewhat east of the center of the peninsula. In the sink-hole region the limestones lie at no great depth. The sinks which form as a result of the solution of the limestones, thus allowing the covering to fall in, usually reach

through to permanent water level, thus forming small circular lakes. In the lake region the calcareous rocks are covered to a greater depth. The lakes are usually circular in outline and are deep, with high banks. In extreme western Florida, including Escambia and Santa Rosa counties, the calcareous deposits are buried beneath the surface to such a depth as not to affect the topography. A similar region is found on the east bank of the Apalachicola River, including Gadsden and the northern part of Liberty counties. Under these conditions the topography is determined by the normal drainage courses.

CLIMATE, TEMPERATURE, AND RAINFALL

The climatic conditions of the state are appreciably influenced by the proximity to oceanic waters. This is especially noticeable with regard to temperature, rainfall, and humidity. The temperature is moderate, the rainfall moderately heavy, and the humidity high. The mean annual temperature near the northern line of Florida is about 67° F., while at Key West in extreme southern Florida the mean annual temperature is close to 77° F. By far the greater part of the state lies within an area which receives between 48 and 57 inches annual rainfall. In extreme southern Florida on the Keys is a small area in which the rainfall is much less, the average for the station at Key West being about 38 inches. On the other hand a small area in extreme western Florida and another along the South Atlantic Coast receives an annual rainfall approximating 60 inches. The average annual rainfall for the state as a whole is close to 54 inches. The rainfall is distributed irregularly throughout the year. The driest months are April and November, while the heaviest rainfall comes as a rule from June to September. Variation in rainfall is pronounced in Florida. This variation is due in part to normal seasonal variations, and in part to the influence of heavy tropical storms, especially those of the late summer and fall. These storms, or hurricanes, which fortunately are not of frequent occurrence, usually result in a heavy precipitation in the belt of country through which they pass.

The maximum recorded precipitation for one year in Florida is probably that of 1912, at which time the rainfall for the state was

64.88 inches (*Climatological Report*, 1912). The maximum for any one station during this exceptional year was 91.61 inches, at Molino in Escambia County. The maximum recorded rainfall for any one month at a single station is 31.26 inches, which is credited to August, although in July, 1916, the rainfall at Bonifay, in Holmes County, was 30.6 inches. The rainfall of a single storm lasting somewhat more than one day has been known to exceed 10 inches. The rainfall for a period of twenty-four hours is known to have been as much at a single station as 13.18 inches. As much as 3.90 inches is recorded as having fallen in one hour at Tampa in August (*Climatological Data*, sec. 84).

DRAINAGE

The drainage conditions in Florida are in some respects exceptional. In that part of the state in which limestones are near the surface, especially on the upland limestone section of the interior, the drainage is largely subterranean, although much of the water that thus enters the earth reappears through large springs which supply streams. In the limestone belt the rainfall enters the earth either directly through the surface materials or through disappearing streams which discharge their flow into porous rocks. The subterranean drainage is best developed in that part of the state known as the "lime sink" region, where aside from the main rivers there are few or no surface streams. Partial subterranean drainage, however, is characteristic of a very much larger area, and for the state as a whole the average for surface run-off is low.

The prevailingly level country over much of the state, together with porous soils, results in but limited surface wash. However, in the more hilly parts of the state the wash of road beds and soils under the influence of heavy rains is sometimes serious.

The streams of Florida for the most part have a slight gradient and are slow-moving. The drainage of the westward extension of the state is through numerous streams, of which the Apalachicola is the largest, having a general north–south direction. The drainage basins of the peninsula are for the most part ill-defined. The St. Johns River, which flows north, and the Kissimmee River, which flows south, receive much of the drainage of the Atlantic slope.

Entering the Gulf of Mexico from the western slope of the peninsula are a number of streams, among which are the Suwannee, Withlacoochee, Hillsboro, and Caloosahatchee rivers.

GEOLOGY

Florida lies entirely within the Coastal Plains province and the formations exposed at the surface are all of the Cenozoic era. The amount of limestone in Florida is relatively large; nevertheless, a

TABLE OF GEOLOGIC FORMATIONS IN FLORIDA

		FEET
Pleistocene	Palm Beach limestone. Marine.	5– 50
	Miami Oölitic limestone. Marine.	10– 50
	Key Largo limestone. Marine.	75–100
	Key West limestone. Marine.	50– 70
	Lostmans River limestone. Marine.	30– 40
	Fort Thompson beds. Marine and fresh water.	0– 20
	Unconformity in places (at least).	
Pliocene	Bone Valley formation. Estuarine.	20–100
	Alachua formation. Residual.	20–100
	Caloosahatchee formation. Marine.	10– 25
	Nashua formation. Marine.	10– 30
Miocene	Choctawhatchee formation. Marine.	30– 50
	Jacksonville formation. Marine.	Thickness undetermined
	Alum Bluff formation. Marine; shallow water.	50–400
	Unconformity where Miocene overlaps Eocene.	
Oligocene	Tampa formation. Marine.	0–130
	Chattahoochee formation. Marine.	100–200
	Vicksburg formation. Marine.	20– 60
	Unconformity in places (at least).	
Eocene	Ocala formation. Marine.	0– 50
	Claiborne formation. Marine.	Thickness not known
	Unconformity.	
Cretaceous	Unknown.	
Comanchean	Known only from well cuttings.	

very considerable quantity of sedimentary material, including sand, clay, and flint pebbles, was carried to the south and included in some of the Florida formations. The progress made in recent years in the study of the geology of Florida has made necessary a number of

changes in the classification of the formations of the state. Of the formation names formerly in use, one or two have been discarded, and on the other hand several new names have been added. The classification which at present best represents our knowledge of the geology of the state is expressed in the table (p. 290). A recently discovered fact in regard to the geology of Florida is the presence of Comanchean formations forming the substructure of the peninsula and extending at least as far west as Tallahassee.[1] Scarcely less remarkable is the complete absence, so far as any records yet obtained indicate, of the Cretaceous formations (Upper Cretaceous). If any of these formations were present they were removed by erosion previous to the deposition of the late Eocene formations. Their absence in any case can be accounted for only by a long period, previous to the late Eocene, during which the Florida land mass stood above water-level. The earth structure by which this peninsular land mass was produced thus dates back at least into the Mesozoic period.

STRATIGRAPHIC SUCCESSION

COMANCHEAN FORMATIONS

The oldest formations that have been recognized in Florida are those encountered in well drilling and known at present only from well cuttings. The fossils found in these cuttings indicate the presence of Comanchean formations under all of the peninsula and a part at least of west Florida. The discussion of these formations together with the data from which they have been determined has been given by Dr. J. A. Cushman in the *Twelfth Annual Report of the Florida Geological Survey*. The thickness of the Comanchean underlying Florida has not been determined. The formations are chiefly limestone. The Cretaceous (Upper Cretaceous) is wanting in all deep wells of which record has been obtained.

EOCENE

The Eocene deposits are represented in Florida by the Claiborne and Ocala formations. The *Claiborne formation* comes into Florida for only a short distance on the Choctawhatchee River near the

[1] Joseph A. Cushman, "The Age of the Underlying Rocks of Florida as Shown by the Foraminifera of Well Borings," *Florida State Geol. Surv., 12th Ann. Rept.*, 1919.

Georgia-Florida border. Where exposed on the Choctawhatchee River this formation consists of a glauconitic calcareous sand rock, exposures of which are seen at intervals on the river banks for about one and two-thirds miles downstream from the Georgia-Florida line, beyond which it passes below the bed of the river. The thickness of this formation in Florida has not been determined.

The *Ocala formation* as developed in Florida consists for the most part of very pure limestone. Fossils are abundant, although many of the mollusks are preserved only as casts. The rock as a rule is granular and porous, although in places, by replacement, it has become close-grained and compact. Masses and layers of flint representing limestone replaced by silica are of frequent occurrence in this formation. Aside from the flint masses much of the rock consists of soft white limestone or shell marl. This formation is exposed to a limited extent on the Chipola River near Marianna, and also over a considerable area in central peninsular Florida. According to recent studies by Cushman the thickness of the formation is very moderate, in places not exceeding 40 or 50 feet.

OLIGOCENE

The Oligocene as limited by recent investigations includes in Florida only the Vicksburg, Chattahoochee, and Tampa formations. The Ocala formation, which had been placed by Dall and others in the Oligocene, has been placed in the Eocene upon the evidence of the molluscan fauna.[1] The Alum Bluff formation on the other hand formerly referred to the Upper Oligocene has been placed in recent years in the Miocene on the evidence of the vertebrates and invertebrates.[2]

The *Vicksburg formation* consists of limestones lithologically not unlike those of the Ocala formation. Exposures of the Vicksburg formation are found in Florida near Marianna and Chipley, in Jackson and Washington counties.

[1] G. Wythe Cooke, "The Age of the Ocala Limestone," *U.S. Geol. Surv., Prof. Paper 95*, 1915, pp. 107–17.

[2] E. H. Sellards, "Fossil Vertebrates from Florida; a New Miocene Fauna; New Pliocene Species; the Pleistocene Fauna," *Florida State Geol. Surv., 8th Ann. Rept.*, 1916, pp. 77–119, 5 pls. Carlotta J. Maury, "Santo Domingo Type Sections and Fossils," *Bull. Amer. Paleontology*, V, No. 30 (1917), Correlation table.

The Chattahoochee and Tampa formations, which apparently are in part at least contemporaneous in deposition, constitute the upper part of the Oligocene as developed in Florida. The *Chattahoochee formation* is well exposed on the Chattahoochee River from the Georgia-Florida state line to Rock Bluff, a distance of about twelve miles. Another considerable belt of exposures of this formation is found extending from the Ocklocknee River to or somewhat east of the Suwannee River, and from near the Georgia-Florida state line to the Gulf border. The formation as exposed on the Apalachicola River includes impure clayey limestones. A rather harder and perhaps more nearly pure limestone phase of the formation shows between the Ocklocknee and Suwannee rivers.

The *Tampa formation* is exposed on the Hillsboro River and on the Manatee River near Tampa. It is likewise a limestone varying in hardness and in purity. The thickness of the Oligocene in Florida is difficult to determine, since there are no surface exposures that afford a measurement of the combined thickness of the formations. The evidence from well records as to the thickness of these beds is at present too indefinite to be of service.

MIOCENE

The Miocene of Florida includes the Alum Bluff, Jacksonville, and Choctawhatchee formations. The *Alum Bluff formation*, formerly referred to the Oligocene, as already noted has been placed in the Miocene on the evidence of the vertebrate and invertebrate fossils. The materials of this formation include calcareous sands and sandstones varying to sandy limestones, calcareous clays, fuller's earth clays, and sands. The conditions under which the formation was deposited were evidently shallow water often in the presence of conflicting currents. This is especially true of the upper part of the formation in which cross-bedding is not uncommon. Fossil plants are found in this formation at the type locality at Alum Bluff. At the fuller's earth mines in Gadsden County there is found a limited although extremely interesting land vertebrate fauna associated with a shallow water invertebrate fauna. Farther to the west on the Choctawhatchee and Yellow rivers the formation

is more distinctly marine and contains an abundant marine invertebrate fauna. In the southern part of the state the deposits which are believed to represent the equivalent of the Alum Bluff formation are distinctly phosphatic. As there developed the formation consists chiefly of shell marl beds in which is included black, brown, and white phosphate pebble.

Deposits found on Black Creek in Clay County and referred to the *Jacksonville formation* are lithologically very similar to the Alum Bluff formation as developed in south Florida, and contain similar phosphate pebble.

The *Choctawhatchee formation* is later in age and overlies the Alum Bluff formation. It is chiefly a loosely cemented shell marl, formed in shallow water and often quite sandy. The surface outcrop of this formation occupies a narrow belt extending in a general east–west direction from west of the Choctawhatchee to somewhat east of the Ocklocknee rivers. In determining the thickness of the Miocene it is necessary to rely on well samples. At Jacksonville the Miocene apparently extends from near the surface (about 33 feet) to possibly as deep as 500 feet, giving for the formations of this period a thickness approximating 450 feet. Probably at least 400 feet of the section of the well at Fort Myers is likewise to be referred to the Miocene, while in the well at Okeechobee the Miocene apparently approximates 400 feet in thickness.

Phosphate in the Miocene.—Phosphate rock in considerable quantity appears for the first time in the Lower Miocene[1] (Alum Bluff formation), the phosphates of both the Alachua and Bone Valley formations having been derived from this formation; the hard rock chiefly by chemical, the land pebble phosphate chiefly by mechanical, segregation.[2] While the processes of concentration to

[1] In a well at Apopka, Florida, described in the *Twelfth Annual Report of the Florida Geological Survey*, Comanchean foraminifera have been identified by Cushman from limestones or marls with which is included a considerable quantity of pebble phosphate through a thickness of about 170 feet. Whether the phosphate belongs in this limestone or has fallen down from a higher level remains to be determined. At no other locality is pebble phosphate found in the Comanchean.

[2] E. H. Sellards, "Origin of the Hard Rock Phosphate Deposits of Florida," *Florida State Geol. Surv., 5th Ann. Rept.*, 1913, pp. 23–66; "The Pebble Phosphates of Florida," *ibid., 7th Ann. Rept.*, 1915, pp. 25–116.

workable deposits can be reasonably well followed there remains the problem of the origin of the phosphate in the Alum Bluff formation itself. The Eocene and Oligocene formations of peninsular Florida, are calcareous, some of them being very pure limestones. During the Lower Miocene, however, the conditions were changed to such an extent that very considerable quantities of land-derived sediments were carried into northern Florida. This change was perhaps gradual, as the lower part of the Alum Bluff formation is more calcareous than the upper part. Likewise the Alum Bluff formation of southern Florida is more calcareous than the same formation in northern Florida. At Alum Bluff, land plants are preserved in this formation, and in the fuller's earth mines are found land vertebrates. In south central Florida more or less shell marl is found in the Alum Bluff formation and in southern Florida a deposit of shell marl of great thickness was accumulated during this time. It seems probable that the phosphates of the Alum Bluff formation, from which in later times were formed the workable phosphate beds of Florida, accumulated through chemical or biochemical processes in the warm shallow seas in which were deposited the great marl beds of the formation.

PLIOCENE

Four formations in Florida, more or less well differentiated, are referred to the Pliocene. These are the Nashua and Caloosahatchee shell marls, and the Bone Valley and Alachua formations. The two first mentioned are marine formations. The *Nashua marls* are well developed on the St. Johns River in Putnam and Volusia counties. The *Caloosahatchee marls* find their typical development on the Caloosahatchee River. Both formations contain an abundant fauna of well-preserved invertebrates. The *Bone Valley formation* which contains the workable pebble phosphate deposits is well developed in Polk and Hillsboro counties. This formation is evidently of shallow-water origin and is in part at least estuarine. It represents material reaccumulated during Pliocene time, derived chiefly from the disintegration of the nearby Miocene deposits. The *Alachua formation* likewise represents a re-working of materials derived from the disintegration chiefly of the Miocene deposits and to some extent also of the older formations on which this formation

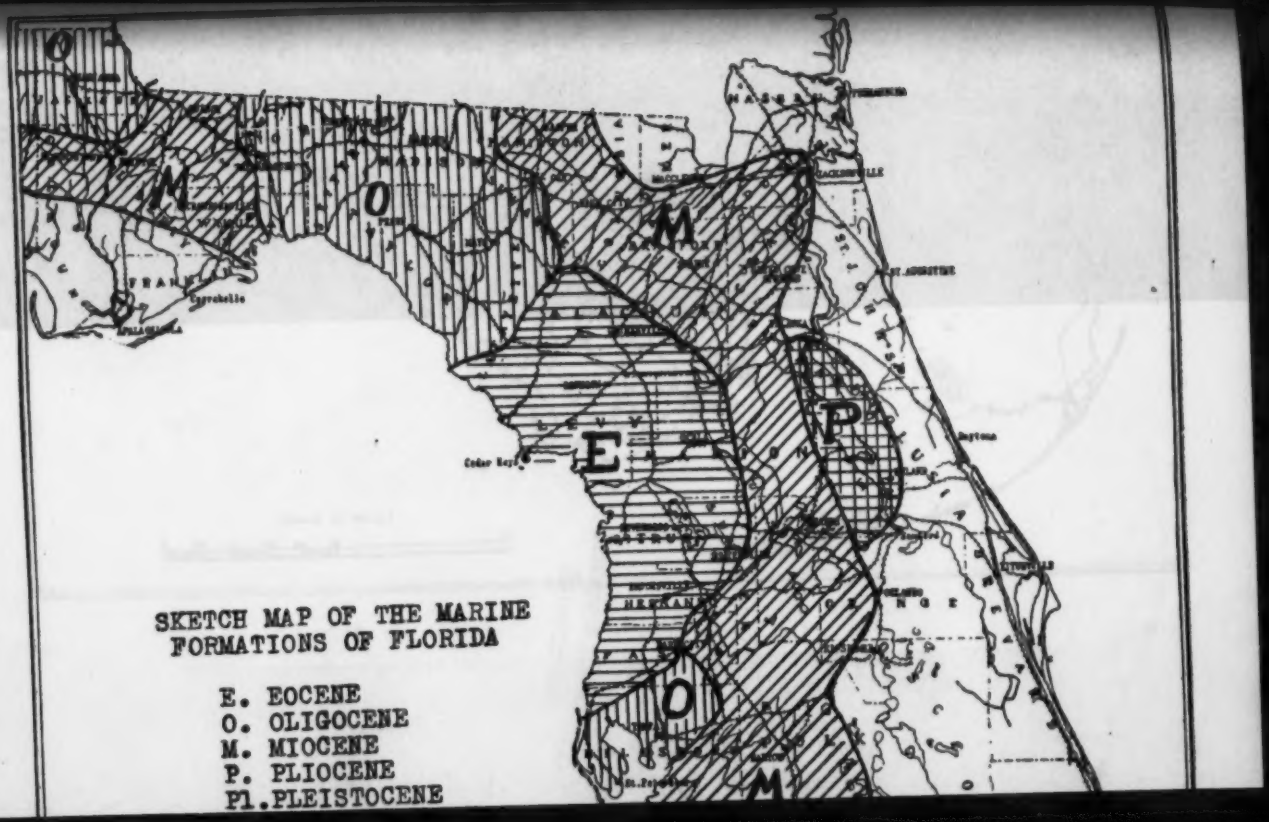
rests. The Alachua formation contains the workable deposits of hard rock phosphate. Both the Bone Valley and Alachua formations contain a vertebrate fauna on the basis of which the formations are referred to the Pliocene. The Bone Valley formation rarely exceeds 100 feet in thickness and as a rule is less. The Dunnellon formation likewise is usually less than 100 feet in thickness. Both the Nashua and Caloosahatchee formations so far as known are thin and may not exceed 50 or 100 feet.

PLEISTOCENE

The Pleistocene formations of Florida include river alluvial and marine deposits. The marine or chiefly marine Pleistocene deposits of the state have been described under the heading of Palm Beach limestone, Miami oölitic limestone, Key Largo limestone, Key West limestone, Lostmans River limestone, and Fort Thompson beds. The five first named are all of marine origin. The Fort Thompson beds include an alternation of fresh-water and marine deposits. All of these deposits are found in southern Florida and the interrelation of the several named units remains to be determined on more detailed stratigraphic work than has yet been done. Alluvial Pleistocene deposits are widely distributed over the state, especially in the stream valleys. In places these stream deposits contain vertebrate and invertebrate fossils.

GEOLOGIC SKETCH MAP

The sketch map (Plate II) shows in a general way the surface distribution of the Florida formations. Owing to the small scale of the map it has been necessary to combine the formations. It is also impracticable to show limited exposures, such for instance as the exposures of the Ocala Eocene on the Chipola River near Marianna, or of the Claiborne Eocene on the Choctawhatchee River near the Georgia-Florida state line. Outliers and remnants of some of the formations are omitted for the same reason. Thus over both the Eocene and the Oligocene of peninsular Florida are found remnants of the Lower Miocene, indicating probably the former extension of the Alum Bluff formation over the entire state. No attempt has been made to show the Alachua formation, which rests chiefly upon the Eocene of Alachua, Levy, Marion, and Citrus


O
M
O
M
E
P
O
M
SKETCH MAP OF THE MARINE FORMATIONS OF FLORIDA
E. EOCENE
O. OLIGOCENE
M. MIOCENE
P. PLIOCENE
Pl. PLEISTOCENE

E. EOCENE
O. OLIGOCENE
M. MIOCENE
P. PLIOCENE
Pl. PLEISTOCENE

Science & Department

counties; nor the Bone Valley formation, which rests upon the Miocene of Polk and Hillsboro counties. The alluvial Pleistocene deposits are likewise omitted from the map, and also the limited exposures of Pliocene (?) on the St. Marys River.

STRUCTURAL CONDITIONS IN THE FLORIDIAN PLATEAU

THE RELATION OF THE FLORIDA PENINSULA TO THE COASTAL PLAIN

An unusual structural feature in coastal plains geology is the great Floridian plateau which, projecting from the mainland, separates the Atlantic Ocean from the Gulf of Mexico. The times of origin of this plateau may not be determinable, although it is now known to have been in existence and to have formed a large shallow-water area as early at least as the Lower Cretaceous or Comanchean period. Although affected by diastrophic agencies, including elevation and depression, this plateau has continued as a structural feature from the Comanchean or earlier to the present time.

For some years the Florida Geological Survey has been collecting well logs and well cuttings with a view to determining so far as practicable the structural conditions underlying peninsular Florida. This work has progressed slowly, although some data have now accumulated that have a very important bearing on this problem. Early in 1918 cuttings containing numerous foraminifera from a deep well then recently completed in Sumter County were sent to Dr. T. W. Vaughan, of the United States Geological Survey, by whom they were referred to Dr. J. A. Cushman. Dr. Cushman's identification of the foraminifera of these samples led to the very unexpected result that they indicated the presence of Comanchean (Lower Cretaceous) formations. Subsequently the foraminifera were identified by Dr. Cushman from the cuttings of about fifteen wells in Florida. In addition there are a number of other wells that from logs or samples give approximate data.

SKETCH MAP OF STRUCTURAL CONDITIONS IN FLORIDA

Upon the basis of all data available at this time there has been constructed a sketch map (Fig. 1) which represents approximately what is known of structural conditions in the peninsular section of

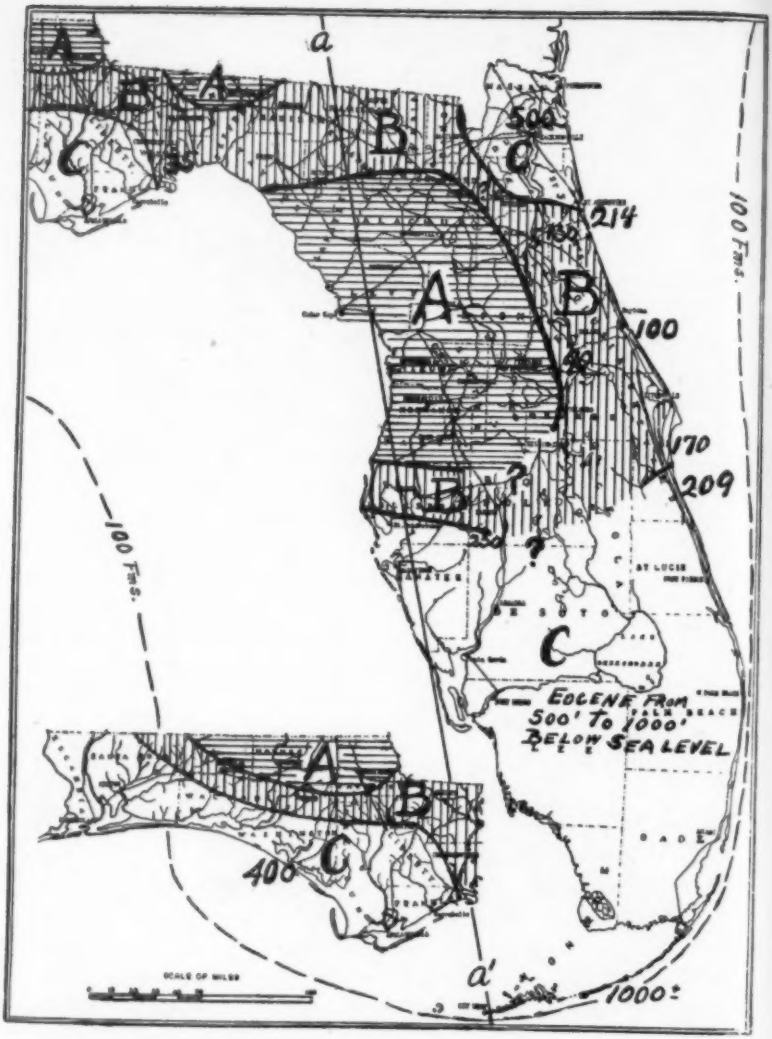


FIG. 1.—Sketch map to indicate general structural conditions in Florida: *A*, Belt of country in which the Eocene formations, when present, lie above sea-level, mostly from sea-level to as much as about 100 feet above; *B*, Eocene formations below sea-level; for the most part between 0 and 200 feet below. Doubtful territory for both belts *A* and *B* is indicated by a question mark; *C*, Eocene formations probably more than 200 feet below sea-level, varying from 200 feet to a maximum, so far as known, of about 1,000 feet in the southern part of the peninsula. Figures entered on the map record the approximate depth to the top surface of the Eocene, usually the Ocala formation. The margins of the Floridian land mass are approximately coincident with the 100-fathom contour, the location of which is indicated on the map. The axis of the land mass is approximately indicated by the line *a*–*a'*.

Florida. On this map there is indicated an area in the west central part of the peninsula, marked "A," in which the top of the Eocene limestones, when present, lies at or above sea-level. The data for placing the eastern margin of this area are very limited, and the boundaries are necessarily very roughly approximated. In the lake region of Clay County in particular it is possible that the Eocene may lie closer to the surface than is here indicated.

A second area, "B," is marked off on the map, in which generally speaking the top of the Eocene limestones appears to lie below sea-level, but at no place in excess of 200 feet below sea. These two areas, it will be noted, together make up a broad belt extending across and occupying all of the north central part of the peninsula from the Gulf to the Atlantic coasts. The data on which this belt is mapped is derived in part from surface exposures and in part from well records. The upper course of the Suwannee River in Florida is known to lie in a structurally low area, since in following the course of this stream it passes toward the Gulf to successively older formations. Since in Hamilton County the Alum Bluff Miocene is exposed at elevations not exceeding 75 feet above sea it is surmised that the Eocene will be found in this general area to lie below sea-level. From numerous wells drilled at Jacksonville it is known that the Eocene limestones there lie about 500 feet below sea-level. On the other hand, at Riverdale, on the St. Johns River about 35 miles south of Jacksonville, Eocene limestones are reached, as indicated by well cuttings, at about 211 feet below sea-level; while at St. Augustine the Ocala Eocene, on the authority of Dr. W. H. Dall, is placed at a depth of 224 feet from the surface or about 214 feet below sea-level.

In the well of Mr. Oliver Gibbs at Melbourne Beach, Eocene fossils were detected which, from the log of the well, appear to have come from the depth of 221 feet, the total depth of the well being 318 feet. At intermediate points between Melbourne and St. Augustine, on and near the coast the Eocene limestones lie, so far as determined, at depths between 100 or somewhat less and 200 feet below sea-level. This is true of wells at Cocoa, where Eocene fossils have been taken from a well the total depth of which does not exceed 190 feet; at New Smyrna, where the Eocene appears from

well samples to have been reached at a depth of 105 feet from the surface; at Daytona, where from well logs it would seem that the Eocene is somewhat shallower than at New Smyrna, lying apparently at less than 100 feet from the surface. The depth to the Eocene has been determined approximately at a few inland towns in this area. At Sanford, fossils of the Ocala formation have been identified by Cushman at a depth of 113 feet. The surface level at the old railway depot at Sanford is given as 20 feet above sea. The surface level at the well is not known but probably does not differ greatly from the level at the depot. The top surface of the Eocene therefore is probably somewhat less than 100 feet below sea-level. At Orange Mills the limestones, probably Eocene, have been reported at a depth of 130 feet, the surface elevation at this place being about 15 feet above sea-level. A slightly increased depth to these limestones is suggested by well records at Hastings.

In the well of the Palmetto Phosphate Company in Polk County the top of the Ocala is placed by Cushman at 360 feet. The surface elevation at Fort Meade is 130 feet above sea. Hence the actual level of the top surface of the Ocala formation is probably somewhat more than 200 feet below sea-level.

That part of the peninsula in which the Eocene formations so far as known lie at a depth of more than 200 feet below sea-level includes a small area in the northeastern part of the state and the whole of extreme southern Florida as well as a coastal belt west of the Apalachicola River. The depth at which the Eocene is known more or less definitely is indicated at several localities within this large area although the data is as yet very limited. There is in particular complete lack of information, as indicated by the use of the question mark on the map, in the southern part of the lake region, where the older formations may be expected to lie rather close to the surface.

ASYMMETRY OF THE FLORIDIAN PLATEAU

The actual position and extent of this plateau, as has been shown by Smith, Vaughan, and others,[1] is strikingly different to that which

[1] Eugene A. Smith, "On the Geology of Florida," *Am. Jour. Sci.* (3), XXI (1881), 292–309; T. Wayland Vaughan, "A Contribution to the Geologic History of the Floridian Plateau," Carnegie Institution of Washington, *Pub. No. 133*, 1910.

appears from the inspection of an ordinary map of the land areas. The 100-fathom contour may be taken as the approximate margin

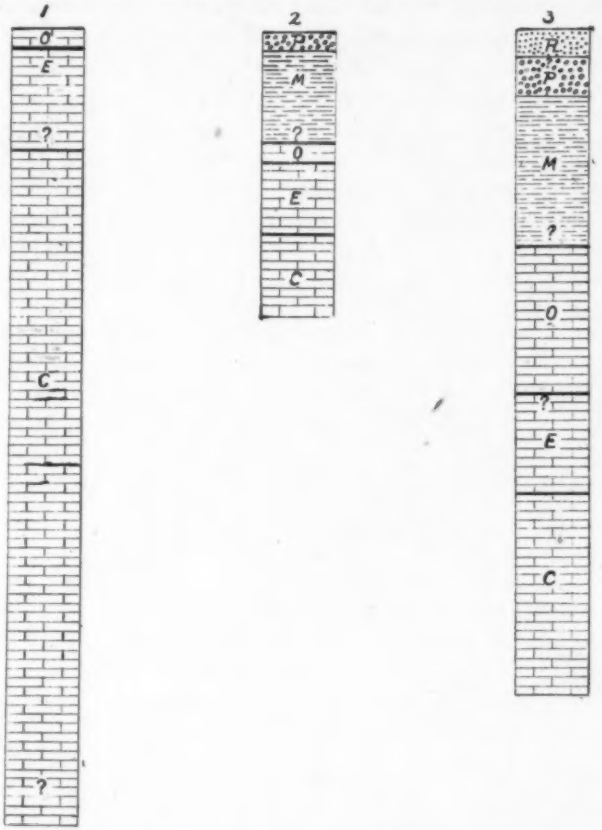


FIG. 2.—Thickness of formations as indicated by wells. Vertical scale, one inch equals 400 feet. No. 1, well in Wakulla County, eastern part of West Florida; No. 2, well of Palmetto Phosphate Company, Polk County, South Central Florida; No. 3, well of Florida East Coast Railway, on the Florida keys, Monroe County, South Florida.

of the plateau, since the slope to this line is for the most part gradual, while beyond this contour the slope is steep, and in places, especially toward the south end of the peninsula, is abrupt. Taking this

100-fathom contour as the margin it will be found that scarcely one-half of the plateau is above water, and that the greater part of that which is above water lies to the east of the north–south axis. With regard to elevation the plateau is therefore asymmetrical, the eastern half being higher, mostly above sea-level, than the western half, which is almost wholly submerged. This lack of symmetry is apparently due in particular to a tilting or warping of the peninsula toward the west, by which the coast of west Florida has been depressed as far south as Hernando County, while the east coast, including all of the southern tip of the peninsula, has been slightly elevated.

RECENT PUBLICATIONS

—VATIN, J. Estadistica Minera de la República, Ano 1915. Ministerio de Agricultura de la Nación. Dirección General de Minas, Geología e Hidrología. Boletin No. 8, Serie A (Minas). [Buenos Aires, 1917.]

—VAUGHAN, T. W. The Reef-Coral Fauna of Carrizo Creek, Imperial County, California, and Its Significance. [U.S. Geological Survey, Professional Paper 98-T. Washington, 1917.]

—WARD, L. KEITH. Annual Report of the Director of Mines and Government Geologist of South Australia for 1916. With maps. [South Australia Department of Mines. Adelaide, 1917.]

—WARING, G. A. Mineral Springs of Alaska, with a Chapter on the Chemical Character of Some Surface Waters of Alaska, by R. B. DOLE and A. A. CHAMBERS. [U.S. Geological Survey, Water-Supply Paper 418. Washington, 1918.]

—Washington Academy of Sciences, Journal of the. Vol. VIII.

—WASHINGTON, H. S. Chemical Analyses of Igneous Rocks Published from 1884 to 1913, with a Critical Discussion of the Character and Use of Analyses (a Revision and Expansion of Professional Paper 14). [U.S. Geological Survey, Professional Paper 99. Washington, 1918.]

—WATKINS, J. A. Occurrence and Mitigation of Injurious Dusts in Steel Works. [U.S. Department of the Interior, Bureau of Mines, Technical Paper 153. Washington, 1917.]

—WATTS, A. S. The Feldspars of the New England and North Appalachian States. [U.S. Department of the Interior, Bureau of Mines, Bulletin 92. Washington, 1916.]

—WELLS, A. E. The Wet Thiogen Process for Recovering Sulphur from Sulphur Dioxide in Smelter Gases. [U.S. Department of the Interior, Bureau of Mines, Bulletin 133. Washington, 1917.]

—Western Australia Geological Survey. Maps and Sections to Accompany Report on Contributions to the Study of the Geology and Ore Deposits of Kalgoorlie, East Coolgardie Goldfield, Part III. Plates I–XIV. [Western Australia Geological Survey, Bulletin 69. Perth, 1917.]

———. Maps and Sections to Accompany Report on the Geology and Ore Deposits of Meekatharra, Murchison Goldfield. Plates I–XXV. [Western Australia Geological Survey, Bulletin 68. Perth, 1916.]

—WHITE, I. C., Assisted by R. V. HENNAN, D. B. REGER, and R. C. TUCKER. Map of West Virginia showing Coal, Oil, Gas, Iron Ore, and Limestone Areas. [West Virginia Geological Survey. Morgantown, 1917.]

—WHITE, J. H. Underground Latrines for Mines. [U.S. Department of the Interior, Bureau of Mines, Technical Paper 132. Washington, 1916.]

—WILLCOX, F. H. Safe Practice at Blast Furnaces: a Manual for Foremen and Men. [U.S. Department of the Interior, Bureau of Mines, Technical Paper 136. Washington, 1916.]

—WILSON, H. M., AND FLEMING, J. R. Organizing and Conducting Safety Work in Mines. [U.S. Department of the Interior, Bureau of Mines, Technical Paper 103. Washington, 1917.]

—WOOD, HARRY O. On Cyclical Variations in Eruption at Kilauea. Second Report of the Hawaiian Volcano Observatory, of the Massachusetts Institute of Technology and the Hawaiian Volcano Research Association. Massachusetts Institute of Technology. [Cambridge, Mass., 1917.]

—WOODBRIDGE, T. R. Ore-Sampling Conditions in the West. [U.S. Department of the Interior, Bureau of Mines, Technical Paper 86. Washington, 1916.]

—WOODS, HENRY. The Cretaceous Faunas of the North-Eastern Part of the South Island of New Zealand. [New Zealand Geological Survey, Palaeontological Bulletin No. 4. Wellington, 1917.]

—YALE, C. G. Gold, Silver, Copper, Lead, and Zinc in California and Oregon in 1916. Mines Report. [U.S. Geological Survey, Mineral Resources of the United States, 1916, Part I: 8. Washington, 1918.]

—YALE, C. G., AND GALE, H. S. Borax in 1916. [U.S. Geological Survey, Mineral Resources of the United States, 1916, Part II: 26. Washington, 1918.]

———. Magnesite in 1916. [U.S. Geological Survey, Mineral Resources of the United States, 1916, Part II: 27. Washington, 1918.]